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The whole is created by the sum of which parts?: using prosopagnosia to determine the visual primitives used in human object recognition

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The whole is created by the sum of which parts? Using prosopagnosia to determine the visual primitives used in human object recognition

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ABSTRACT

Some contemporary theories of basic level object recognition posit visual object recognition through the use of structural descriptions (i.e., a form of representation in which objects are represented in terms of their parts and the categorical relations among the parts). Much empirical evidence exists supporting this suggestion, yet no empirical investigation has determined the exact visual primitives and categorical relations used in the structural descriptions that humans use for visual object recognition. The current study attempts to identify the exact visual primitives used in basic level object recognition by testing a prosopagnosic patient's ability to discriminate visual primitives. According to the Coordinate Relations Hypothesis (Cooper & Wojan, 2000), individuals with prosopagnosia should perform normally relative to controls when discriminating visual primitives that are coded distinctly from one another by the visual system, but should be impaired relative to controls when discriminating visual primitives that are coded the same way. Nine studies investigated a prosopagnosic's ability to discriminate visual primitives (geons, Biederman, 1987) relative to controls. The results indicate that not all of the features defining visual primitives proposed by Biederman are coded uniquely in the human visual system, suggesting that the alphabet of visual primitives used for object recognition is comprised of fewer than the 36 geons proposed by Biederman. In particular, the results suggest that the features of axis curvature, size change of the cross section (constant vs. expanding; constant vs. expanding & contracting), and cross section symmetry (reflectional & rotational vs. reflectional; reflectional & rotational vs. asymmetrical; reflectional vs. asymmetrical)

are used to define the visual primitives in object recognition, whereas the features of cross section curvature, and size change of the cross section (expanding vs. expanding & contracting) are not.

INTRODUCTION

Of the myriad cognitive tasks that humans perform, the process of object recognition represents a particularly interesting case because of the relative ease with which it occurs and the relative complexity of the obstacles that must be overcome to enable effective object recognition. In particular, the visual system must take as input a theoretically infinite number of possible visual scenes, and produce as output a functional and finite set of labels that apply to individual stimuli within the scene. For example, a small room containing a chair, desk, lamp, stool, fan, and umbrella could potentially be viewed from an infinite number of possible positions, and yet, from nearly any viewing position, a viewer would likely be able to effortlessly and correctly identify each of the objects in the room. Among contemporary theories of object recognition, some suggest that recognition occurs through the identification of a basic set of visual primitives from which objects are composed (Biederman, 1987; Marr, 1982). Sets of specific visual primitives, or building blocks necessary for effective object recognition have been proposed, but never formally tested. The current research represents an attempt to empirically identify the specific visual primitives used for basic level object recognition.

Theories of Object Recognition

For any theory of object recognition to be useful, the theory must be able to account for the observable properties of human object recognition performance. Two properties in particular must be considered when developing such a theory. First, a theory of how human object recognition takes place must be able to account for the fact that humans can easily and effortlessly recognize a wide range of objects, including objects that they have never seen before, as belonging to a particular category. For example, when an automobile manufacturer releases a new model of vehicle such as a pickup truck, observers can recognize the new model as a pickup truck just as easily and quickly as recognizing a pickup truck that they have seen before. Therefore, any theory of human object recognition must be sufficiently general that it allows humans to correctly categorize new objects.

Second, a theory of how human object recognition occurs must be able to account for the fact that humans are capable of recognizing objects from any perspective. Changes in the spatial relationship between the viewer and an object can result in rather large changes in the image being projected to the retina, yet recognition performance is rarely impaired in such cases. Consider the example of the room containing a chair, desk, lamp, stool, fan, and umbrella; each of these objects is capable of being recognized from nearly any perspective. It is not the case that humans can recognize a chair from one position, but that upon walking around to the other side of the chair, can no longer do so. This property of the visual system is often referred to as viewpoint invariance and has been demonstrated using a variety of visual recognition tasks (Biederman & Gerhardstein, 1993; O'Kane, Biederman, Cooper, & Nystrom, 1997). Given this property of the visual system, any theory of human object recognition must include a mechanism general enough to allow for recognition of the same object from any viewpoint.

Numerous theories of human object recognition, varying in both content and sophistication, have been proposed over the years, including template theories (Ullman, 1989; Vetter, Hurlbert, & Poggio, 1995; Vetter, Poggio, & Bültoff, 1994), feature theories (Selfridge, 1959), and structural description theories (Biederman, 1987; Marr, 1982). Of the theories that have been proposed, structural description theories have been championed as not only the most explanatory, but also as the most widely investigated within the realm of object recognition (Hummel, 2000; Kurbat, 1994).

According to structural description theories, objects are represented in memory in terms of a set of visual primitives and the categorical relationships among those visual primitives. For example, the structural description of a mug might be, "a curved cylinder to the side of a cylinder." Notice that the structural description specifies both the parts of the object as well as the categorical relations between the parts. By proposing that the visual system stores objects in this manner, the theory can explain how humans are able to recognize novel examples of objects, as well as recognize objects from nearly any perspective. By using a structural description of "curved cylinder to the side of a cylinder," to identify a mug, the system is capable of classifying any object that fits that particular structural description as a mug (i.e., the system is capable of recognizing novel examples of objects). Further, assuming that the perspective from which the object is viewed allows the viewer to identify the parts and categorical relationships between the parts of the object, the viewer will be able to extract a structural description that will allow recognition (i.e., a structural description representation is able to account for viewpoint invariance).

Recognition by Components.

Among the structural description theories that have been proposed, arguably the most influential has been Recognition by Components (RBC) (Biederman, 1987).

According to RBC, object recognition occurs via a process of segmenting images into simple geometric components and identifying the categorical relationships between those components. What makes RBC particularly useful among structural description theories is that it posits a small set of components referred to as geons (short for "geometrical icons"), which act as the visual primitives for any object. According to Biederman, geons can be defined by four easily identifiable properties of a visual shape: symmetry of the cross section, size change of the cross section, edge curvature of the cross section, and curvature of the longest axis. More specifically, Biederman (1987) proposed a set of 36 geons defined by taking all possible combinations of the following four major parameters: the symmetry of the cross section (reflectional and rotational vs. reflectional only vs. asymmetrical); the size change of the cross section along the length of the axis (constant vs. expanding vs. expanding and contracting); the edge curvature of the cross section (straight vs. curved); and the curvature of the longest axis (straight vs. curved) (see Figures 1 & 2). The specific properties that Biederman (1987) used to define the geons were based on computational rather than empirical considerations. These specific properties were chosen because they can all be determined for a particular shape regardless of the viewer's perspective on the shape. Because the properties defining the geons can be determined from any viewpoint, they would allow object recognition to achieve viewpoint invariance.

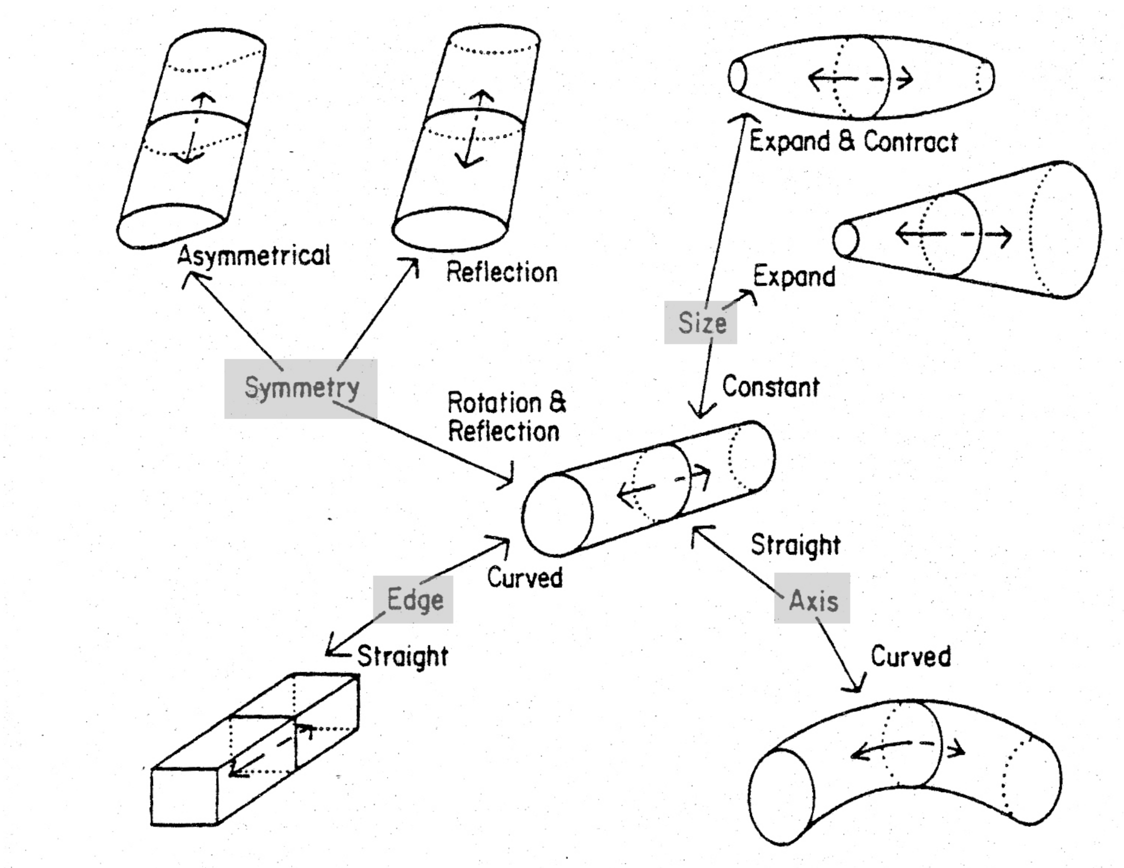
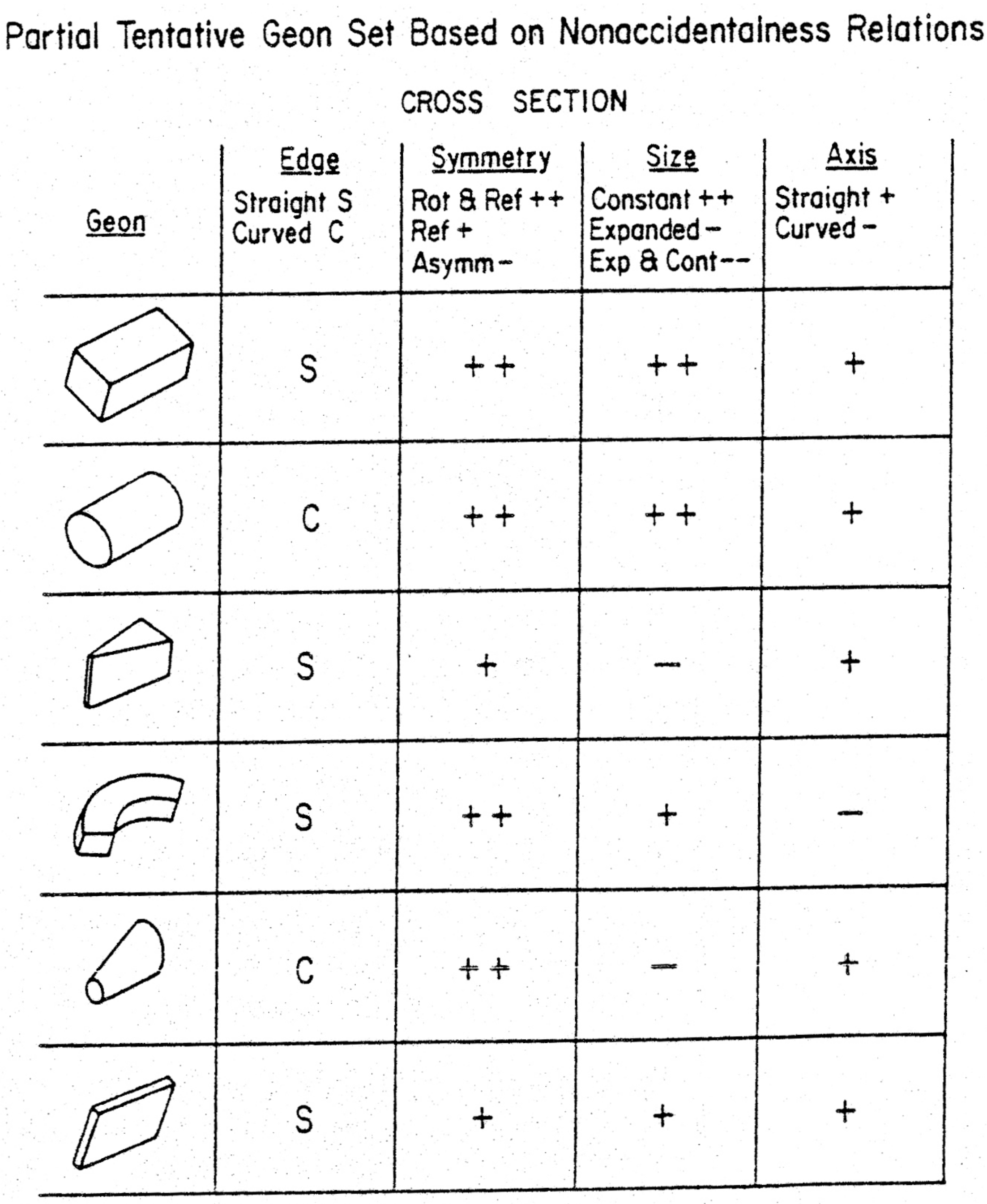


Figure 1. Possible parametric variations of Biederman's geons (Biederman, 1987). The four primary parameters are highlighted in gray, with arrows pointing to each possible variation of that particular parameter.



Partial Tentative Geon Set Based on Nonaccidentalness Relations

CROSS SECTION

Geon	Edge Straight S Curved C	Symmetry Rot & Ref ++ Ref + Asymm −	Size Constant ++ Expanded − Exp & Cont −−	Axis Straight + Curved −
	S	++	++	+
	C	++	++	+
	S	+	−	+
	S	++	+	−
	C	++	−	+
	S	+	+	+

Figure 2. Sample of possible geons based on various parameters (Biederman, 1987).

In addition to positing a set of basic visual primitives, RBC also identified a set of basic categorical relationships for specifying the relations of the visual primitives to one another in an object. The categorical relationships between the geons of an object posited by RBC included their relative size, relative position, and relative orientation. RBC predicts that if the geons and the categorical relationships between the geons can be extracted from an image, recognition should occur uninhibited. Biederman (1987) refers to this process as the Principle of Componential Recovery.

Biederman (1987) made a persuasive argument for the sufficiency of 36 geons acting as the visual primitives used for identification of any basic object, but provided no empirical evidence that the 36 geons proposed by RBC are in fact the visual primitives actually used for recognizing objects. The purpose of the current research is to empirically test each of the properties that RBC posits are used to define the visual primitives used in human object recognition. To understand the method by which the properties will be tested, it is first necessary to discuss an inherent limitation of using a structural description representation to perform visual recognition tasks.

As previously noted, an account of human object recognition that represents objects using structural descriptions solves two major difficulties that any object recognition system must overcome, namely generalization to novel exemplars, and viewpoint invariance. However, structural description theories are incapable of explaining an easily observable, prevalent property of human object recognition: humans are capable of visually discriminating between objects that *share* the same structural description (e.g., discriminating between two mugs, two pickup trucks, two human faces, etc.). Whereas a structural description theory like RBC provides a good account of how different examples of an object can be placed into the same basic level class despite metric variations, the theory says nothing about how objects sharing structural descriptions can be discriminated from one another.

Coordinate Relations Hypothesis

To address this problem encountered by RBC, Cooper and Wojan (2000) proposed the Coordinate Relations Hypothesis, which suggests that object recognition occurs via two separate and neurologically dissociable processes. According to the Coordinate Relations Hypothesis, basic level object recognition utilizes a structural description representation, coding parts of objects and their categorical relations to one another, just as RBC would suggest, whereas discrimination between objects that share the same structural description is achieved through the use of a second system that codes the precise metric features of objects, thus allowing for within structural description discriminations. The first system, or *structural description system*, is referred to by Cooper and Wojan as the categorical system, and operates quickly and efficiently for nearly all basic level object recognition tasks. The second system, or *coordinate system*, which codes the precise metric properties of objects, would be more computationally intensive, and is used predominantly when the recognition task calls for discrimination between two objects that share structural descriptions. For example, in identifying a human face, the categorical system would store the parts of the face and the categorical relationships between those parts (e.g., the left eye is to the side of the right eye, above and to the side of the nose, and above and to the side of the mouth), whereas the coordinate system would store the parts of a face in reference to some arbitrary fixed reference point (e.g., the left eye is 4 units below, and 2.5 units to the right of the reference point) (see Figure 3).

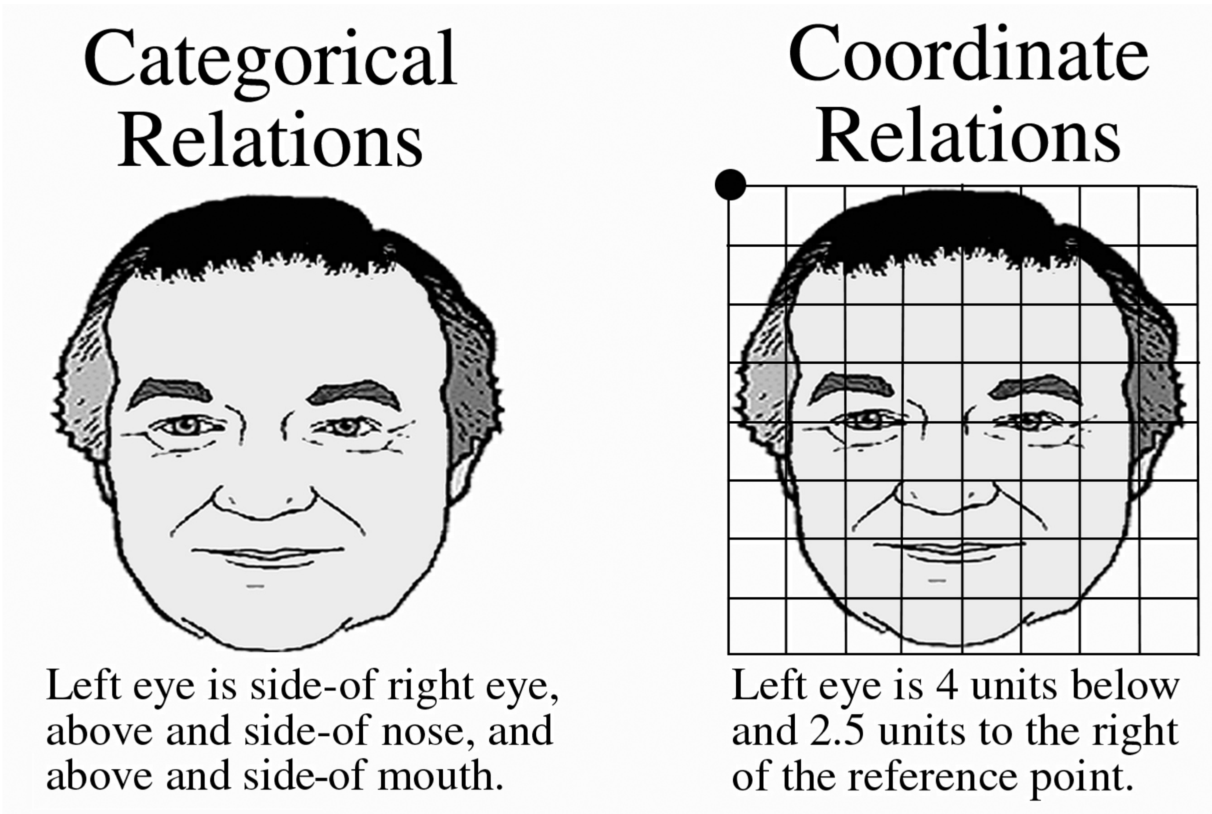


Figure 3. Coding of a human face using the categorical recognition system (left), and the coordinate recognition system (right). The categorical recognition system codes the positions of the parts of a face relative to one another without specific reference to precise distances. The coordinate recognition system codes the precise positions of the parts of a face relative to a fixed reference point (Cooper & Wojan, 2000).

Using a variety of paradigms to test this hypothesis, Cooper and colleagues have provided support for the existence of two separate recognition systems, a categorical system used for basic level object recognition, and a coordinate system used for discriminating between objects that share structural descriptions (Brooks & Cooper, 2006; Cooper & Brooks, 2004; Cooper & Wojan, 2000).

The recognition of individual faces is a classic case of a recognition task for which the Coordinate Relations Hypothesis would predict the coordinate recognition system would be used. Because all faces share the same parts and categorical relations between the parts, a system using structural descriptions would be incapable of discriminating between individual faces. In support of Cooper and Wojan's (2000) distinction between recognition systems, a growing body of evidence suggests that the process of face recognition utilizes a recognition system separate from that of basic level object recognition, and that the process occurs in a specific area of the fusiform gyrus of the right hemisphere, referred to as the fusiform face area (FFA) (Clark, Keil, Maisog, Courtney, Ungerleider & Haxby, 1996; Farah, Levinson, & Klein, 1995; Kanwisher, McDermott, & Chun, 1997; Puce, Allison, Asgari, Gore, & McCarthy, 1995; Puce, Allison, Asgari, Gore, & McCarthy, 1996). Because much of the research on the psychological and neurological dissociation of these two systems has focused on basic level object recognition versus face recognition, the system responsible for discriminating between two objects that share the same structural description has come to be referred to as the "face recognition system." Although additional theories have been proposed regarding the specific recognition functions mediated by the "face recognition" system, including recognition of biological stimuli (Cappa et al., 1998; Caramazza & Shelton, 1998; Chao, Haxby, & Martin, 1999, Chao, Martin, & Haxby, 1999), recognition of objects within the same subordinate level category (Damasio, Damasio, & Van Hoesen, 1982; Gauthier, Anderson, Tarr, Skudlarski, & Gore, 1997; Gauthier, Skudlarski, Gore, & Anderson, 2000; Marsolek, 1999), and recognition of objects for which observers are experts (Diamond & Carey, 1986; Gauthier et al., 2000; Gauthier & Tarr, 1997; Tarr & Gauthier, 2000), the Coordinate Relations Hypothesis can account for the results supporting each of these competing theories, whereas the reverse is not true, (see Casner, 2006 for review). Additional evidence for two dissociable recognition systems, one for most basic level object recognition tasks, and one for face recognition comes from neuropsychological studies of patients with a visual disorder known as prosopagnosia.

Prosopagnosia

Prosopagnosia is defined as an inability to recognize faces of familiar people on the basis of visual perception, despite the absence of low-level visual impairments or cognitive impairments such as dementia or amnesia (Mayer & Rossion, 2005). Further, prosopagnosic patients are capable of recognizing people through other cues such as voice, gait, size, clothes, or even distinctive features such as moustache, scars, or commonly worn accessories (Mayer & Rossion, 2005). Although unable to recognize familiar faces, prosopagnosic patients retain semantic knowledge about individuals, such as demographic information and personal history (e.g., number of children, type of employment, and manner of personal affiliation with the patient).

Prosopagnosia is most commonly acquired as the result of stroke or brain trauma resulting from automobile accidents (Mayer & Rossion, 2005). Brain lesions causing prosopagnosia are generally located in the infero-medial part of the temporo-occipital area in the right hemisphere (RH), in the fusiform gyrus, the lingual gyrus, and the posterior parahippocampic gyrus (Damasio et al., 1982; Grüsser &

Landis, 1991). In particular, areas in the inferior occipital gyrus (IOG) of the right hemisphere, and the lateral part of the middle fusiform gyrus (often referred to as the "fusiform face area" or FFA) of the right hemisphere, appear to respond preferentially to faces, and are typically damaged in prosopagnosic patients (Kanwisher et al., 1997; Rossion et al., 2000; Sergent Ohta, & MacDonald, 1992). Recent analyses of prosopagnosic studies have found maximal lesion overlap in the right IOG (Bovier & Engel, 2005). According to Bouvier and Engel, the most common co-occuring deficit with prosopagnosia is achromatopsia (the inability to see colors resulting from cortical damage). Also, most prosopagnosic patients have visual field deficits, often located in the left upper quadrant (Mayer & Rossion, 2005). Another common deficit in prosopagnosic patients is topographical disorientation (impairments in angle and distance processing, and loss of environmental familiarity) (Aguirre, & D'Esposito, 1999).

By studying patients with prosopagnosia, researchers are able to test hypotheses regarding whether a particular visual recognition task uses either the basic level recognition system or the face recognition system (Farah et al., 1995; Kanwisher et al., 1997). Based on studies using individuals with prosopagnosia (Casner, 2006; Casner, Cooper, O'Brien & Brooks, 2006; Farah et al., 1995; O'Brien, Cooper, Casner, & Brooks, 2006), as well as individuals with normally functioning visual systems (Caramazza & Shelton, 1998; Chao, Martin, & Haxby, 1999; Diamond & Carey, 1986; Gauthier et al., 2000), it appears that the FFA is used for visual tasks other than face recognition.

In line with the finding that the FFA is used for tasks other than face recognition, the Coordinate Relations Hypothesis makes specific predictions about the types of recognition tasks in addition to face recognition at which prosopagnosic patients should show deficits. Specifically, the Coordinate Relations Hypothesis predicts that prosopagnosic patients should show deficits relative to controls with any task in which objects with the same structural descriptions must be discriminated. Whereas theories such as those proposed by Farah et al. (1995) suggest that prosopagnosia may result in problems with within category discriminations, no theory other than the Coordinate Relations Hypothesis predicts problems discriminating within structural descriptions, regardless of whether the objects belong to the same basic level category.

Testing the Coordinate Relations Hypothesis in a Patient with Prosopagnosia

To test the hypothesis that prosopagnosic patients show deficits relative to controls with any task in which objects with the same structural descriptions must be discriminated, not just face discriminations, Casner (2006), Casner et al. (2006) and O’Brien et al. (2006) conducted a number of visual discrimination studies comparing the recognition performance of prosopagnosic patient LB against the performance of a control group. In multiple experiments, Casner (2006) compared prosopagnosic patient LB to controls with normally functioning visual systems on two different types of discrimination tasks. In each of the experiments, one condition required discriminations between objects defined by different structural descriptions, whereas the other condition required discriminations between objects defined by the same structural description. In both experiments, images were presented sequentially, and the task of the participants was to indicate via button press as quickly and accurately as possible whether the images were examples of the same species (Experiment 1), or were physically identical (Experiment 2). For example, in Experiment 1, LB and controls discriminated between animals defined either by different structural descriptions (e.g., a dog and an eagle, which are composed of different parts and categorical relationships between the parts), or the same structural description (e.g., a wolf and a lion, which are both composed of the same parts and categorical relationships between the parts) (see Figure 4).

In Experiment 2 of Casner (2006), LB and controls discriminated between line drawings of objects with the same name defined by either different structural descriptions (e.g., a rectangular table and an oval table), or the same structural description (e.g., a short rectangular table and a long rectangular table). According to RBC, a rectangular table would be defined as a brick above four elongated bricks, whereas an oval table would be defined as a cylinder above four elongated bricks. On the other hand, both a short rectangular table and a long rectangular table would be defined as a brick above four elongated bricks. (See Figure 5 for examples from Experiment 2 in Casner, 2006).

Figure 4. A dog and an eagle are defined by *different* structural descriptions (top), whereas a wolf and a lion share the same structural description (bottom). From Casner (2006).

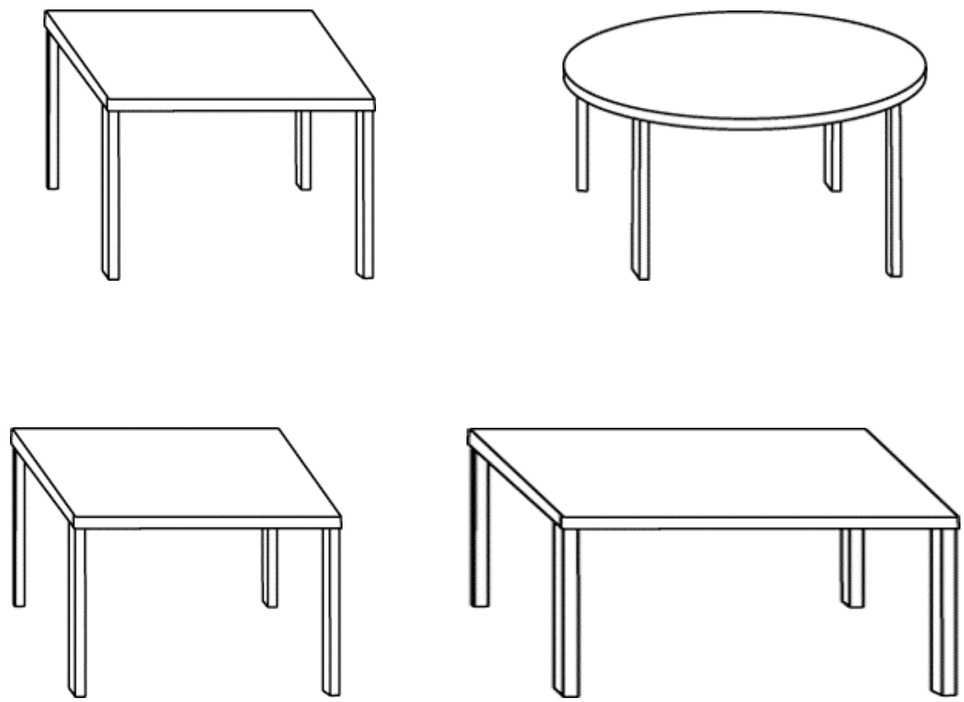


Figure 5. Objects with the same name, defined by *different* structural descriptions (top two tables). Objects with the same name defined by *the same* structural description (bottom two tables). From Casner (2006).

In each of Casner's (2006) experiments, the prosopagnosic performed equivalently to the controls at tasks that involved discriminating between structural descriptions, but showed large deficits any time she had to make comparisons within a structural description (see Table 1). The results strongly supported the hypothesis that prosopagnosia produces deficits in any recognition task requiring discriminations between objects that share the same structural descriptions. In terms of the Coordinate Relations Hypothesis, this pattern of results suggests that prosopagnosia is the result of damage to the coordinate recognition system.

	Error rates on between structural description discriminations		Error rates on within structural description discriminations	
Experiment	Controls	LB	Controls	LB
1	2.4%	2.9%	27.0%	58.8%
2	6.2%	9.4%	10.1%	32.8%

Table 1. Summarized data from Experiments 1 and 2 from Casner (2006). In both experiments, when making discriminations between objects that did not share structural descriptions (columns 1 & 2), LB performed as well as controls, but when making discriminations between objects that shared the same structural description (columns 3 & 4) LB performed much worse than controls.

Current Study

The research proposed here is based on the predictions of the Coordinate Relations Hypothesis (Cooper & Wojan, 2000) and the findings of Casner (2006), Casner et al. (2006), and O'Brien et al. (2006). Recall that RBC (Biederman, 1987) suggested that basic level object recognition occurs via the use of 36 visual primitives called geons and the categorical relations between those geons. As previously mentioned, Biederman's 36 geons were proposed entirely on computational grounds and have never been empirically tested to determine whether they constitute the actual visual primitives used for basic level object recognition. The goal of the current study is to empirically determine whether the 36 geons proposed by Biederman constitute distinct visual primitives, each coded separately by the human visual system, or whether the basic building blocks of object recognition are defined by a set other than that proposed by Biederman's RBC.

Logic of Experiments.

The current research used the findings of Casner (2006) as a foundation for identifying the properties of visual primitives that are coded by the human visual system. Casner's findings suggested that prosopagnosia is the result of damage to the coordinate recognition system, and as such, patients with prosopagnosia should have difficulties discriminating between any objects that share the same structural description. Note, however, that in Casner's studies prosopagnosic patient LB was unimpaired at tasks that utilized the categorical recognition system. Therefore, the logic of the current research is that by comparing the ability of prosopagnosic patient LB relative to controls at discriminating between the geons proposed by Biederman (1987), the results can theoretically provide evidence as to whether each of the individual geons are coded as distinct visual primitives in the human visual system. On the one hand, because prosopagnosic patient LB shows severe deficits discriminating between objects sharing structural descriptions, if two different one-part objects are coded by the visual system as being the same primitive, LB would be expected to show deficits relative to controls when discriminating between those objects. On the other hand, if two one-part objects are coded by the visual system as different primitives, LB would be expected to perform normally compared to controls when discriminating between those objects.

In all the experiments reported here, a group of control subjects and a prosopagnosic were shown two two-part objects back to back and had to decide whether the two objects were physically identical to one another or not. On the trials in which the objects were not identical, sometimes the objects differed because one of the objects' parts was longer in one object than in the other, however the two objects contained exactly the same geons according to Biederman (1987). These are the “different object, same geons” or DSG trials. On other trials in which the two objects were different, the objects differed because one of the parts in the two objects had been changed to a different geon by altering one of the properties that Biederman (1987) proposes defines the different geons. For example, a “cylinder” geon in the first object might have the curvature of its cross section changed from curved to straight and therefore become a “brick” geon in the second object. These trials are called “different object, different geons” or DDG trials. In the eight experiments reported here, each experiment tests a different one of the parameters that Biederman (1987) proposes define the geons by altering a different property in the DDG trials.

Based on the predictions of the Coordinate Relations Hypothesis (Cooper & Wojan, 2000), and the results of Casner (2006), the prediction for the current experiments was that to the extent that LB would have difficulty discriminating between objects that are different from one another, she would show more pronounced deficits when discriminating between objects that have not undergone a primitive change (i.e. objects that share a structural description) relative to those that have undergone a primitive change (i.e. objects that have different structural descriptions). Further, to the extent that LB performs more poorly on DSG trials than on DDG trials, she should perform disproportionately more poorly on the DSG trials than the DDG trials relative to controls. It is this interaction pattern (see Figure 6) that will provide evidence that a particular feature is used to define the visual primitives used in object recognition.

In addition, and perhaps more interestingly, there was no need for a priori predictions regarding which of the features used by Biederman to define his geons are used by the shape recognition system to code visual primitives, because the pattern of results collected from LB and controls can indicate which of the features are used by the shape recognition system to identify individual visual primitives (geons). If it is the case that all of the parameters identified in Figure 1 are used to define the visual primitives used for human shape recognition as Biederman (1987) suggests, then each of the 36 geons proposed by Biederman should be distinctly coded by the human shape recognition system.

Because LB's basic-level shape recognition abilities are intact, if the 36 geons proposed by Biederman are coded as distinct visual primitives by the visual system, LB would be expected to perform as well as controls when discriminating between two objects composed of different primitives (DDG trials), but would be expected to perform poorly compared to controls when discriminating between two objects composed of the same primitives that contain only metric differences (DSG trials).

Suppose, however, that some of the parameters that have been proposed by Biederman are not coded by the shape recognition system, and are not used to define the visual primitives for object recognition. In this case, in addition to performing poorly compared to controls when discriminating between two objects composed of the same primitives with only length differences between the parts, LB would also be expected to perform poorly compared to controls when discriminating between any two objects composed of primitives that differ in a parameter that is <u>not</u> used to classify the visual primitives in the shape recognition system.

For example, suppose that Biederman's (1987) distinction of cross section curvature (straight vs. curved) is, in fact, used to define the visual primitives used in visual object recognition. Given this scenario, the prediction is that in the experiment testing cross section curvature (Experiment 1), LB should perform as well as controls when discriminating objects defined by different structural descriptions (i.e., different object, different geons trials, or DDG trials), but should perform poorly relative to controls when discriminating between objects that share the same structural description (i.e., different object, same geons trials, or DSG trials) (see Figure 6). The factor of greatest interest is the potential interaction between controls' and LB's scores on DDG trials, and controls' and LB's scores on DSG trials. Figure 6 illustrates such an interaction.

Conversely, suppose that Biederman's (1987) distinction of axis curvature (straight vs. curved) is not used to define visual primitives used in object recognition. Given this scenario, the prediction is that in the experiment testing axis curvature, LB should perform worse than controls on both types of tasks (different object, different geons trials (DDG), and different object, same geons trials (DSG)) (see Figure 7). Notice the absence of an interaction pattern between controls' and LB's scores on DDG and DSG trials in Figure 7.

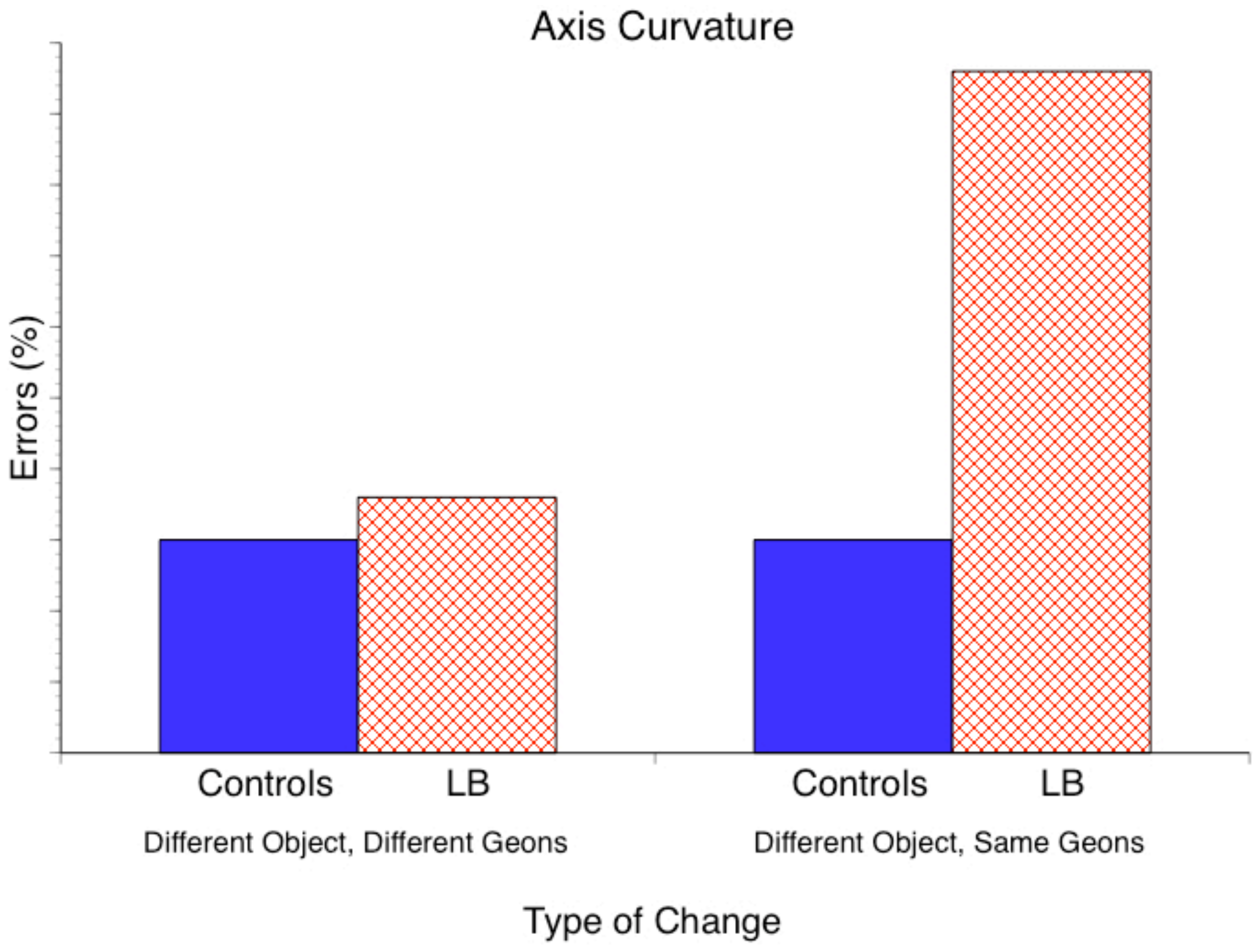


Figure 6. Graph showing how the hypothetical data should appear if cross section curvature is, in fact a feature used by the shape recognition system to define the visual primitives used in object recognition. LB should perform similar to controls when discriminating between two objects in which one object contains a geon with a curved cross section and the other contains a geon with a straight cross section (DDG trials), but should perform much worse than controls when the two objects are composed of the same geons (and are defined by the same structural description) (DSG trials).

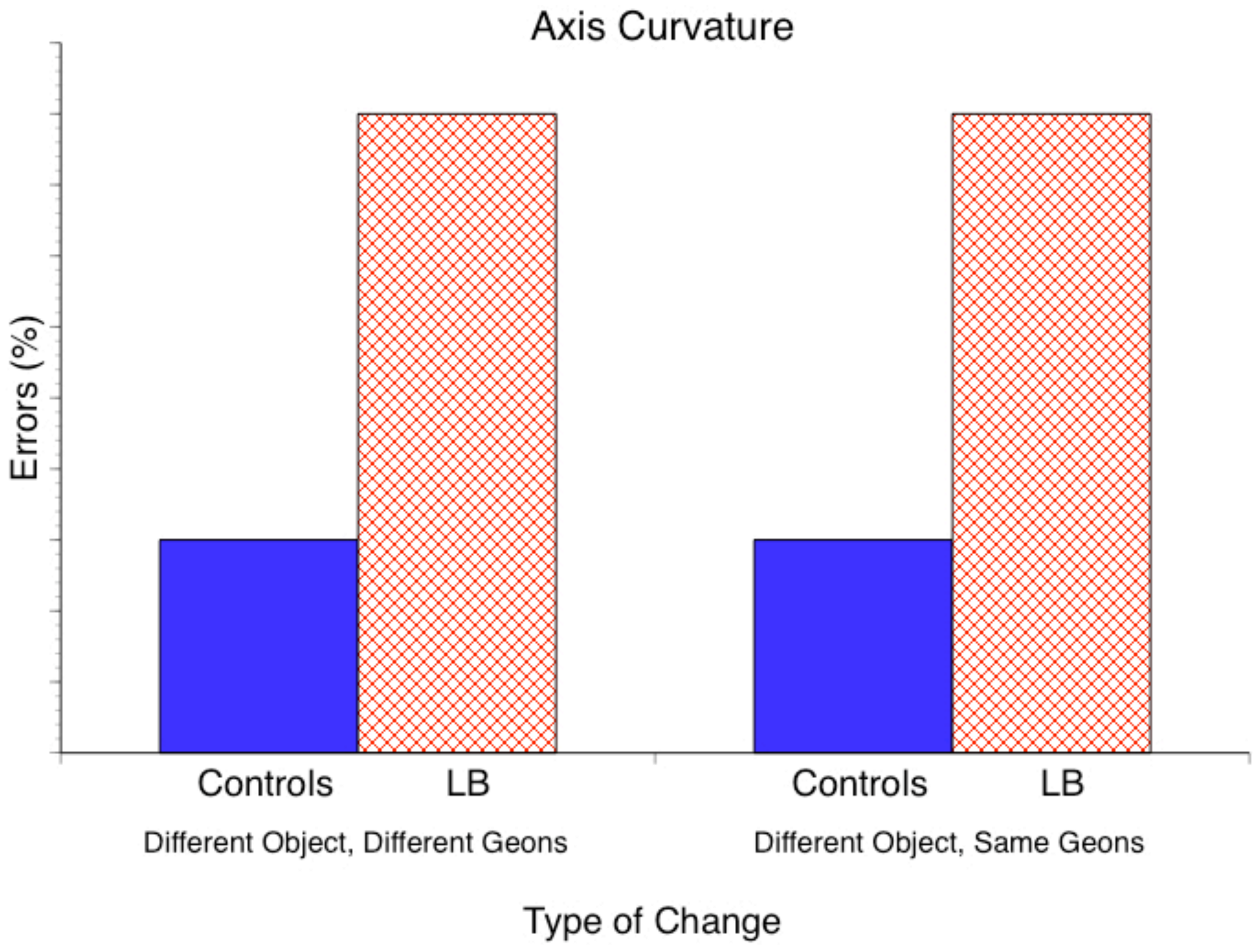


Figure 7. Graph showing how the hypothetical data should appear if axis curvature is not a feature used by the shape recognition system to define the visual primitives used in object recognition. LB should perform poorly relative to controls when discriminating not only between two objects in which one object contains a geon with a curved cross section and the other contains a geon with a straight cross section (DDG trials), but should also perform much worse than controls when the two objects are composed of the same geons (and are defined by the same structural description) (DSG trials).

In each of nine experiments reported here, one of the four major properties that define Biederman's (1987) geons was tested (axis curvature, edge curvature, symmetry of the cross section, and size change of the cross section along the length of the axis) (see Figure 1).

EXPERIMENT 1

Experiment 1 tested whether axis curvature (straight vs. curved) is a defining feature of the visual primitives used for object recognition (see Figure 1).

Method

Participants

Prosopagnosic patient. LB, a 42-year old retired junior high math teacher, suffered a posterior cerebral artery stroke at age 39, resulting in bilateral inferiortemporal damage and partial unilateral right hemisphere hippocampal damage. LB has subsequently been diagnosed with prosopagnosia, achromatopsia (i.e., color blindness), anomia (i.e., a naming deficit), topographical disorientation, right upper quadrantanopia (i.e., blindness in the right upper quadrant of visual field) and left homonymous hemianopia (i.e., blindness in the left half of the visual field). In the remaining intact quadrant of her visual field (the lower right quadrant), LB has normal visual acuity. Since the time of her stroke, LB exhibits evidence of some general memory problems, such as memory for dates and names, recent conversations, and other similar episodic memories. LB's semantic memory, procedural memory, and motor skills are intact. LB spontaneously reported visual recognition problems with faces, skin abrasions, some types of food, plants, animals, buildings (particularly distinguishing between similar looking houses or office buildings), and money (such as telling play money from real money). LB's pattern of deficits (achromatopsia, topographical disorientation, and visual field defect) and neurological damage closely match those typically reported in cases of acquired prosopagnosia (see Bouvier & Engel, 2005, and Mayer & Rossion, 2005 for reviews). LB's occasional anomia (naming deficit) is likely the result of her slight unilateral hippocampal damage. Also worth noting, because only one quarter of LB's visual field is properly receiving visual information, she often needs multiple eye saccades to collect enough visual information to mediate recognition.

Controls. Sixteen Iowa State University undergraduates (10 female) (mean age 21) with no visual or mental impairments served as the control participants. Despite the lack of age matching, utilization of undergraduates as controls for prosopagnosic patients is a relatively routine practice (De Gelder, Bachoud-Levi, & Degos, 1998; Farah, et al., 1995; Farah, Wilson, Drain, & Tanaka, 1995; Gauthier, Behrmann, & Tarr, 1999; Marotta, McKeeff, & Behrmann, 2002).

Test of Prosognosia. Prior to testing, LB was given a test of famous face recognition constructed for the purpose of verifying the diagnosis of prosopagnosia. The test of famous face recognition included identification of 18 grayscale photographs of famous actors, politicians, and athletes, who were chosen to maximize ease of identification. LB's score on the test of famous faces was six correct out of 18 as compared to a mean correct score of 16.6 out of 18 for controls, thus confirming the diagnosis of prosopagnosia.

Test of Object Agnosia. Prior to testing LB was also given a test to verify that she is capable of basic-level object recognition. The test included identification of 18 grayscale photographs of common objects, which were chosen to maximize ease of identification. LB's score on the test of basic-level object recognition was 16 correct out of 18 (the two errors were most likely due to poor contrast of the items) as compared to a mean correct score of 17.9 out of 18 for controls, thus confirming that LB did not meet the criterion for diagnosis of object agnosia.

Stimuli and Materials

Biederman's (1987) geons were rendered using a 3-dimensional rendering program (http://www.blender.org) according to the parameters specified by Biederman (1987) and described in the Introduction (see Figure 1). Because the basic design of the experiments required comparison between sequentially presented images, it was important to control for any abnormal strategies that participants may have developed to aid in visual discrimination (i.e. attending only to overall length, size, or other individual feature). To control for this possibility, all stimuli were objects composed of two geons. By creating two-geon objects and presenting changes in either of the two geons, participants were unable to complete the discrimination tasks by focusing on only one feature of the object. Thirty-six individual two-part objects comprising Biederman's set of geons served as the base stimuli for eight experiments. Each object consisted of two geons—one large geon, and a second small geon, whose identity was randomly chosen, approximately half the size of the large geon (see Figure 8). For controls, all stimuli were presented on a Macintosh G4 computer from a distance of approximately 50 cm, occupying a visual angle of approximately 18°. For LB, all stimuli were presented on a 14" Macintosh iBook laptop computer from a distance of approximately 30 cm, occupying a visual angle of approximately 18°. The experiment was designed and executed using Superlab v4.0.3.

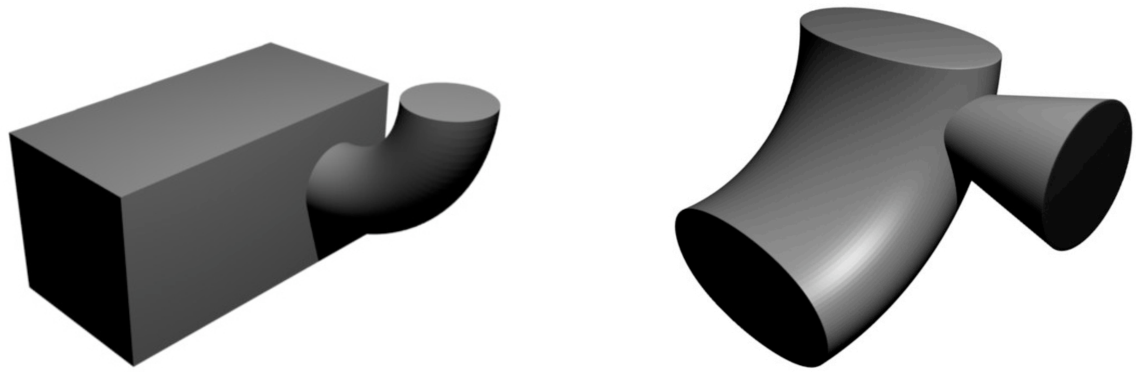


Figure 8. Sample two-part objects composed of two different geons.

Design and Procedure

Trials proceeded as follows: a fixation cross was presented for 500 ms, followed by an initial two-geon object presented for 1000 ms, followed by a 500 ms mask, followed by a second two-geon object presented until participant response (see Figure 9). The first image was presented at central fixation, and the second image was presented in one of eight possible different positions, approximately 12° of visual angle from the position of the first image. This eliminated participants' ability to make simple size or shape discriminations as a result of maintaining focus at a particular point on the screen. The position of the second two-geon object was chosen randomly on each trial by the experimental program. The task of the participant was to determine via button press, as quickly and accurately as possible, whether the two sequentially presented images were physically identical or not,.

Participants were first given 16 practice trials that matched the design of the experimental trials, but used objects made of geon combinations not used in the experimental trials.

Experiment 1 consisted of 288 trials, 144 trials in which physically identical objects were sequentially presented (“identical” trials), and 144 trials in which physically different objects were sequentially presented (“different” trials). Each of the “different” trials contained one of two different types of change between the first and second images. One type of change was a purely metric change in which one of the geons composing the second two-part object became longer or shorter, but remained the same geon. Trials containing this type of change are referred to as “different object, same geons,” (DSG) trials. The alternative type of change was a geon change in which one of the geons composing the second two-part object was replaced by a new geon. Trials containing this type of change are referred to as “different object, different geons,” (DDG) trials. In Experiment 1, because axis curvature was the feature under investigation, in the DSG trials, the larger of the two geons composing the object in the first image was replaced by a metrically lengthened or shortened version of the same geon in the second image (see Figure 9a). In the “different object, different geons” (DDG) trials, if the geon to be replaced was defined by a straight axis in the first image, it was replaced by a geon defined by a curved axis in the second image, and vice versa (see Figure 9b).

Figure 9a.

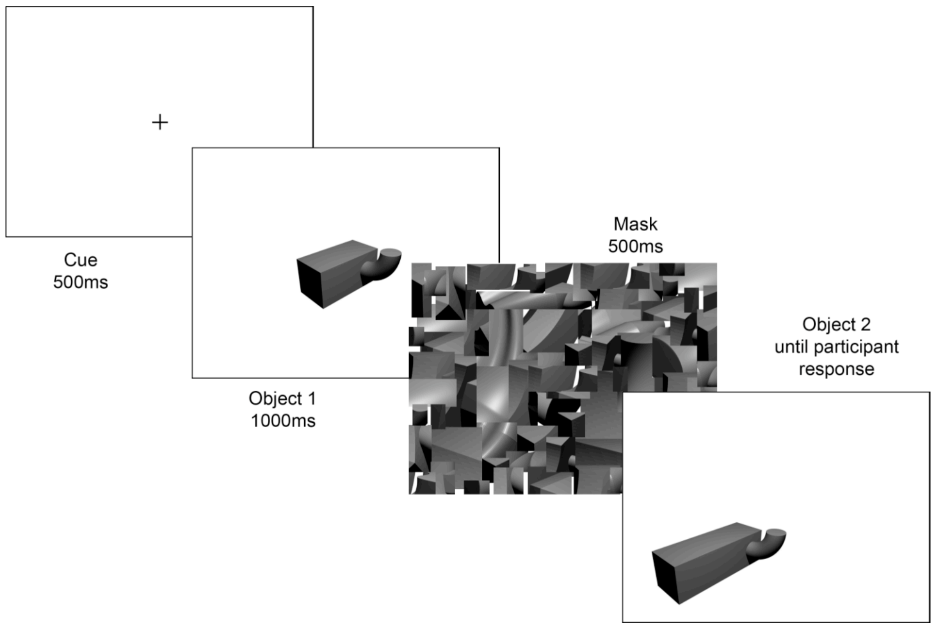


Figure 9b.

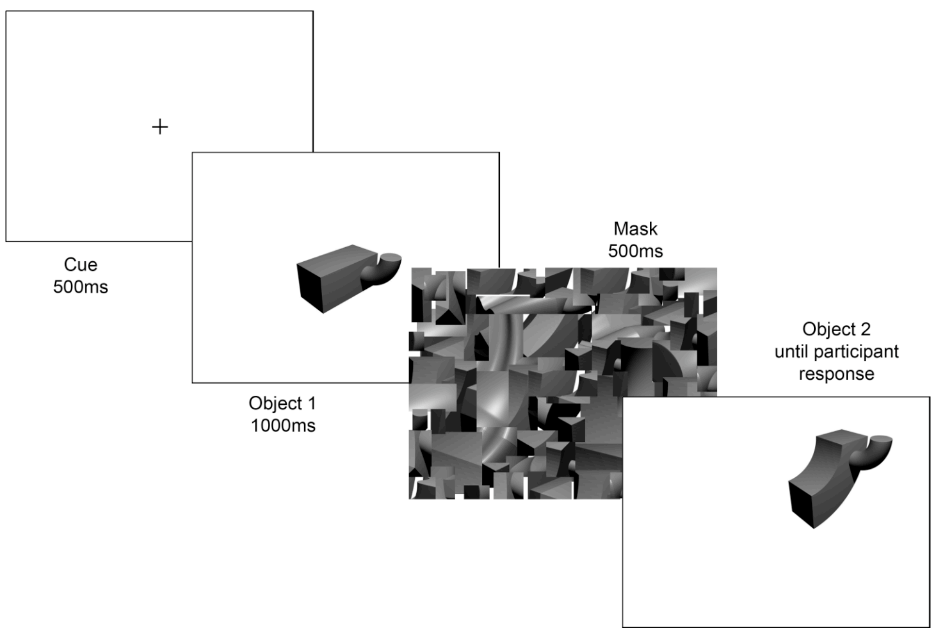


Figure 9. Example trials from Experiment One testing axis curvature (straight vs. curved). Different object, same geons (DSG) trial, in which the larger of the two geons becomes metrically longer from the first object to the second (9a); different object, different geons (DDG) trial, in which the larger of the two geons is defined by a straight axis in the first object, and a curved axis in the second object (9b).

In addition, on the DDG trials, in which one of the geons present in the first object is replaced by a new geon in the second object, the change occurred randomly in the large geon position half of the time (36 trials) (Figure 10a), and in the small geon position half of the time (36 trials) (Figure 10b).

This manipulation of sometimes changing the large and sometimes changing the small geon was included to address a common criticism of research conducted with neuropsychological patients. The criticism suggests that performance differences between controls and neuropsychological patients in psychological tests might be a result of overall task difficulty rather than localized cortical damage. For instance, if a researcher finds that patients with a specific type of cortical lesion are able to perform addition as well as controls, but are much worse at performing multiplication than controls, at least two explanations can account for the data. It may be the case that the area of the cortex lesioned in the group of neuropsychological patients is involved in multiplication but not addition, or it may be the case that as a result of the lesion, the neuropsychological patients' normal cognitive functioning is inhibited such that, as the difficulty of a task increases, they are simply less capable of effectively performing, regardless of the specific nature of the task (in this example, the assumption is that multiplication is more difficult than addition). In regard to the current set of experiments, past research has indicated participants with normally functioning visual systems are more likely to make errors on discriminations between objects that share the same structural description (DSG trials), than on discriminations between objects that do not share structural descriptions (DDG trials), suggesting that discriminating between objects that share

Figure 10a.

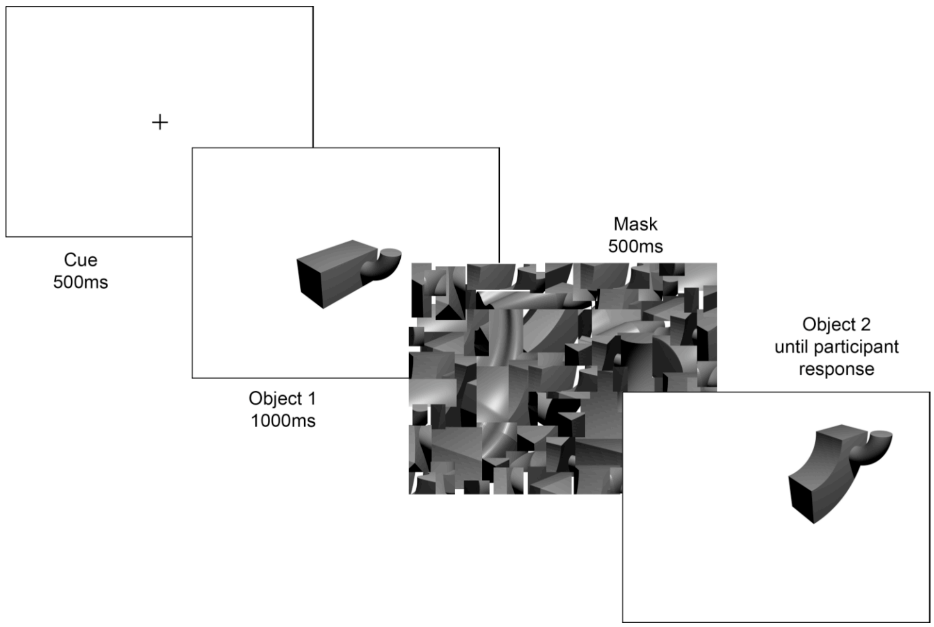


Figure 10b.

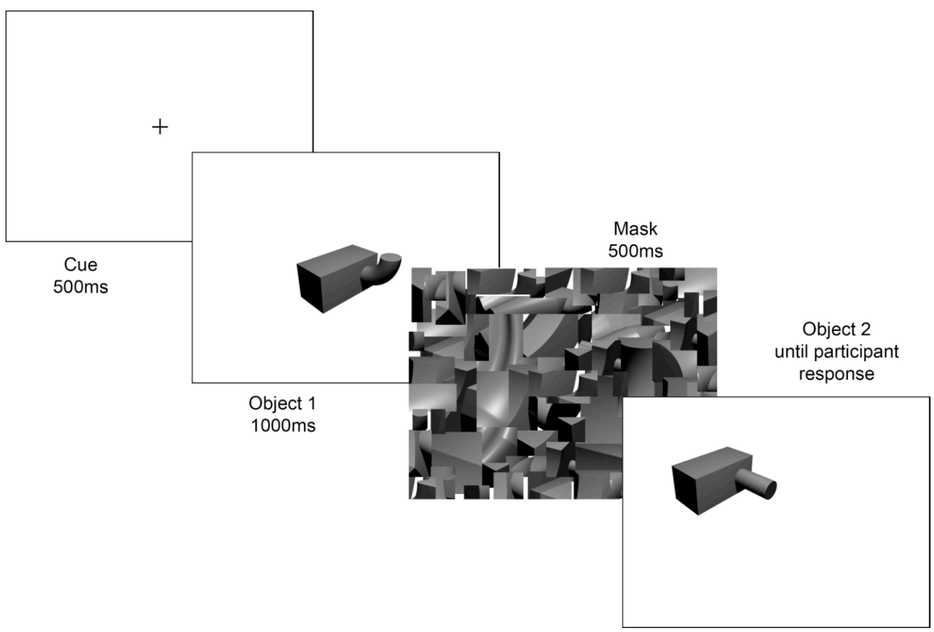


Figure 10. Example trials from Experiment One testing axis curvature (straight vs. curved). "Different object, different geons" (DDG) trial in which the *larger* of the two geons comprising the object is defined by a straight axis in the first image, and by a curved axis in the second image (10a); "Different object, different geons" (DDG) trial in which the *smaller* of the two geons comprising the object is defined by a curved axis in the first image, and by a straight axis in the second image (10b).

the same structural description is a more difficult task for all people (Casner, 2006; Casner et al., 2006; O'Brien et al., 2006; O'Brien et al., 2007). To identify the factors that influence the relative difficulty of discriminations between objects that share the same structural description, and discriminations between objects that do not share structural descriptions, O'Brien, Cooper, & Kahl (2007) conducted a pilot study with control participants, they found that discriminations between two-geon objects that do not share structural descriptions (DDG trials), which are composed of one large geon and one small geon, are more difficult when the change occurs in the position of the smaller geon, relative to when the change occurs in the position of the larger geon. Thus, by including DDG trials in which the change occurs in the either the position of the large geon, or the position of the small geon, the data can be analyzed such that the aforementioned criticism might be addressed. If the difficulty level of the DDG trials is increased to the point that controls' performance on DDG trials matches their performance on DSG trials, and the interaction pattern shown in Figure 6 is still obtained, the possibility that any interactions in the data are the result of task difficulty rather than deficits specific to the coordinate recognition system can be eliminated.

Results

As is typical when comparing the mean scores of a control group to a single neuropsychological patient, a test of a single sample mean was used to determine whether LB's performance, as measured by error rates and reaction times, differed reliably from the performance of controls when discriminating between objects composed of parts defined by straight versus curved axes, that either did or did not share the same geons. Because of LB's visual field deficits, she must spend additional time scanning the presented images to achieve recognition, and as a result her reaction times are consistently slower than those of the controls across all conditions. While reaction time data are reported, the principal dependent variable of interest in the current studies is error rate, and as a result, reaction time data are only useful in that they allow a test of whether any differences in error rates across conditions between LB and controls are a result of a speed-accuracy trade-off.

Error Data.

The error data for Experiment 1 are presented in Figure 11. Although the differences between controls' and LB's mean error rates are significant for both the "different object, different geons" (DDG) task and "different object, same geons" (DSG) task, the pattern of interest is the significant interaction, in which LB's overall performance relative to controls is poor, but her performance relative to the controls is disproportionately worse when discriminating between different objects made of different geons (DDG trials), than when discriminating between different objects made of the same geons (DSG trials), $t(15) = -2.35$, $p < .05$.

Reaction Time Data.

The reaction time data for all Experiments are presented in the Appendix. Because the general patterns of the reaction time data match those of the error rate data in each experiment, suggesting that neither the controls nor LB were sacrificing accuracy for response speed, no further discussion of reaction time data will be included.

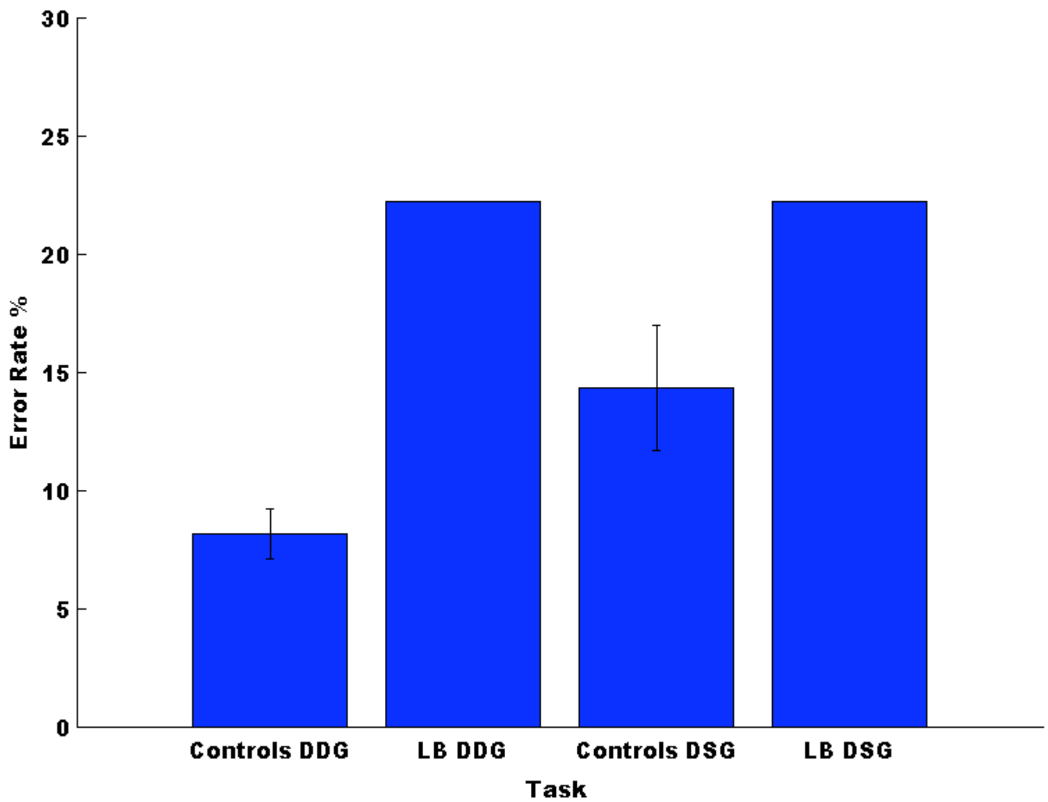


Figure 11. Mean error rates for controls and LB in Experiment 1, testing axis curvature (straight vs. curved). DDG represents "different objects, different geons" trials, and DSG represents "different objects, same geons" trials. Error bars on the control subjects' data represent the standard error of the mean.

Discussion

Given the predictions of the Coordinate Relations Hypothesis, as well as the findings of Casner (2006) with patient LB, the pattern of results from Experiment 1 suggest that perhaps the curvature of the cross section of a visual primitive is not used to define the visual primitives used for object recognition. The prediction was that if curvature of the cross section is a property that allows the human visual system to distinguish between two visual primitives, LB should have performed as well as controls on trials comparing different objects composed of different geons (specifically, geons that were different only in the curvature of their axes) (DDG trials), but should have performed much worse than controls on trials comparing different objects composed of metrically elongated or shortened versions of the same geons (DSG trials) (see Figure 6 for the predicted pattern of data if the feature being tested is used to define visual primitives). The results show that not only did LB perform worse than controls in both DSG trials, and DDG trials, but also that her error rates for both tasks were identical (identically poor), suggesting that both tasks are mediated by the same recognition system (the coordinate recognition system, which is damaged in patients with prosopagnosia) (see Figure 7 for the predicted pattern of data when the feature being tested is not used to define visual primitives). By implication, this suggests that axis curvature (straight vs. curved) is not a parameter used by the human visual system for discriminating between visual primitives.

However, this is not the only plausible explanation for the results. These data can also potentially be accounted for by considering LB's specific impairments and more closely examining the conditions in Experiment 1. Recall that the "different object, different geons" condition consisted of two types of comparison trials. One type of trial presented an initial object, followed by a secondary object (to which the participant responded), in which the larger of the two geons had been replaced. The other type of trial presented an initial object, followed by a secondary object, in which the smaller of the two geons had been replaced (see Figure 10). It is possible that because of LB's visual field deficits, her ability to efficiently scan the initial image of presentation, which is only presented for 1000 ms, is impaired, and as a result, she is less likely than controls to effectively scan and encode the smaller of the two geons comprising the object. In a post-experimental interview, LB revealed that she did feel as if the initial image was presented too quickly for her to effectively scan and encode the entire object on every trial.

To examine this possibility, a test of a single sample mean was conducted on only the “different object, different geons” (DDG) trials in which the larger of the two geons changed from the first image to the second (see Figure 12).

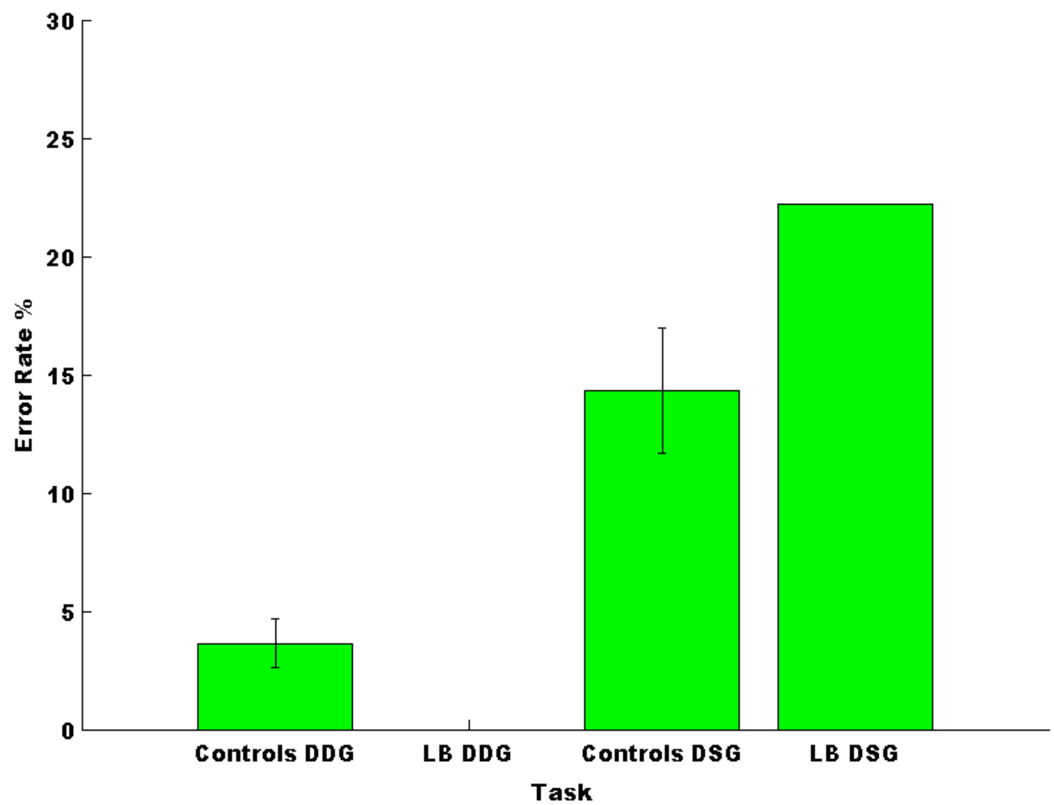


Figure 12. Mean error rates for controls and LB in Experiment 1 showing *only* “different object, different geons” (DDG) trials in which the larger geon of the two-geon objects changed. “Different object, same geons” (DSG) trials data are also presented. Error bars on the control subjects’ data represent the standard error of the mean.

By comparing the DDG trials in which only the large geon of the two-geon objects changed to the DSG trials, a pattern different from that obtained when analyzing all of the DDG trials emerges. The new pattern more closely resembles the pattern predicted to emerge when a particular feature is used by the shape recognition system to identify visual primitives used in object recognition (see Figure 6 for predicted pattern). The data in Figure 12 illustrate a significant interaction whereby LB is disproportionately worse at discriminating between objects that share the same structural description (DSG trials) than discriminating between objects that do not share the same structural description (DDG trials) relative to controls, $t(15) = 5.88$, $p < .05$. As previously mentioned, this interaction suggests that the curvature of the axis (straight vs. curved) is a feature used by the shape recognition system to define visual primitives used in object recognition.

Analyzing the DDG trials in which only the large geon of the two-geon objects changed produced a different pattern of results, which suggests that LB's visual field and scanning deficits may have influenced her ability to effectively encode both geons on the initially presented image. Because the sequence of the images presented in Experiment 1 began with a fixation cross about which the first image is centered (see Figure 8), it is reasonable to conclude that if LB is only able to encode one geon of the two-geon objects during the 1000 ms presentation of the initial image, she is likely encoding only the larger of the two geons. If this is the case, analysis of the difference in mean error rates for the DDG trials in which only the larger of the geons is changed will likely provide a more accurate representation of LB capabilities. However, to be sure, an additional test is necessary in which the initial image in the trial sequence remains on the screen for enough time to be fully encoded by LB. If by providing more time for scanning and encoding, LB's error rates for all of the DDG trials more closely matches her error rates from Experiment 1 for the DDG trials in which only the larger of the geons changes, justification will be provided for any conclusions based on the analyses done with only the DDG trials in which the larger of the two geons changes. This matter is dealt with at length in the general discussion.

Given the illuminating nature of examining the data for Experiment 1 based on whether the DDG trials included geon changes at both the large and small position, or only the large position, all further reports of results will include analyses of "different object, different geons" (DDG) trials in which all geon changes are present, as well as "different object, different geons" (DDG) trials in which only the large geon change is present, in addition to "different object, same geons" (DSG) trials. A discussion of how this problem might be addressed in future research is included in the general discussion.

EXPERIMENT 2

Experiment 2 tested whether edge curvature of the cross section (straight vs. curved) is a defining feature of the visual primitives used in object recognition (see Figure 1).

Method

Participants

Participants in Experiment 2 (both controls and LB) were identical to those in Experiment 1.

Stimuli and Materials

All materials in Experiment 2 were identical to those in Experiment 1. The stimuli used in Experiment 2 were the same as those used in Experiment 1, except that on DDG trials, rather than comparing objects in which the first object had a geon defined by a straight axis, and the second object had a geon defined by a curved axis (or vice versa), DDG trials compared objects in which the first object had a geon defined by a curved cross section, and the second object had a geon that is defined by a straight cross section (or vice versa). See Figure 13 for example trials.

Design and Procedure

The design and procedure for Experiment 2 were identical to Experiment 1, except that on DDG trials, one of the objects' parts changed cross section curvature rather than axis curvature.

Results

Error Data

The error data for Experiment 2 are presented in Figure 14. Just as in Experiment 1, the results generated by analysis of the DSG and all of the DDG trials indicate an interaction, $t(15) = -8.41$, $p < .05$, where one of the tasks is disproportionately more difficult for LB than for controls, but once again, the direction of the interaction surprisingly suggests that LB had more difficulty with DDG trials than with DSG trials, which contradicts the predictions of the Coordinate Relations Hypothesis, as well as the results of Casner (2006). By looking at only the DDG trials in which the larger geon changed however, a different pattern emerged (see Figure 15).

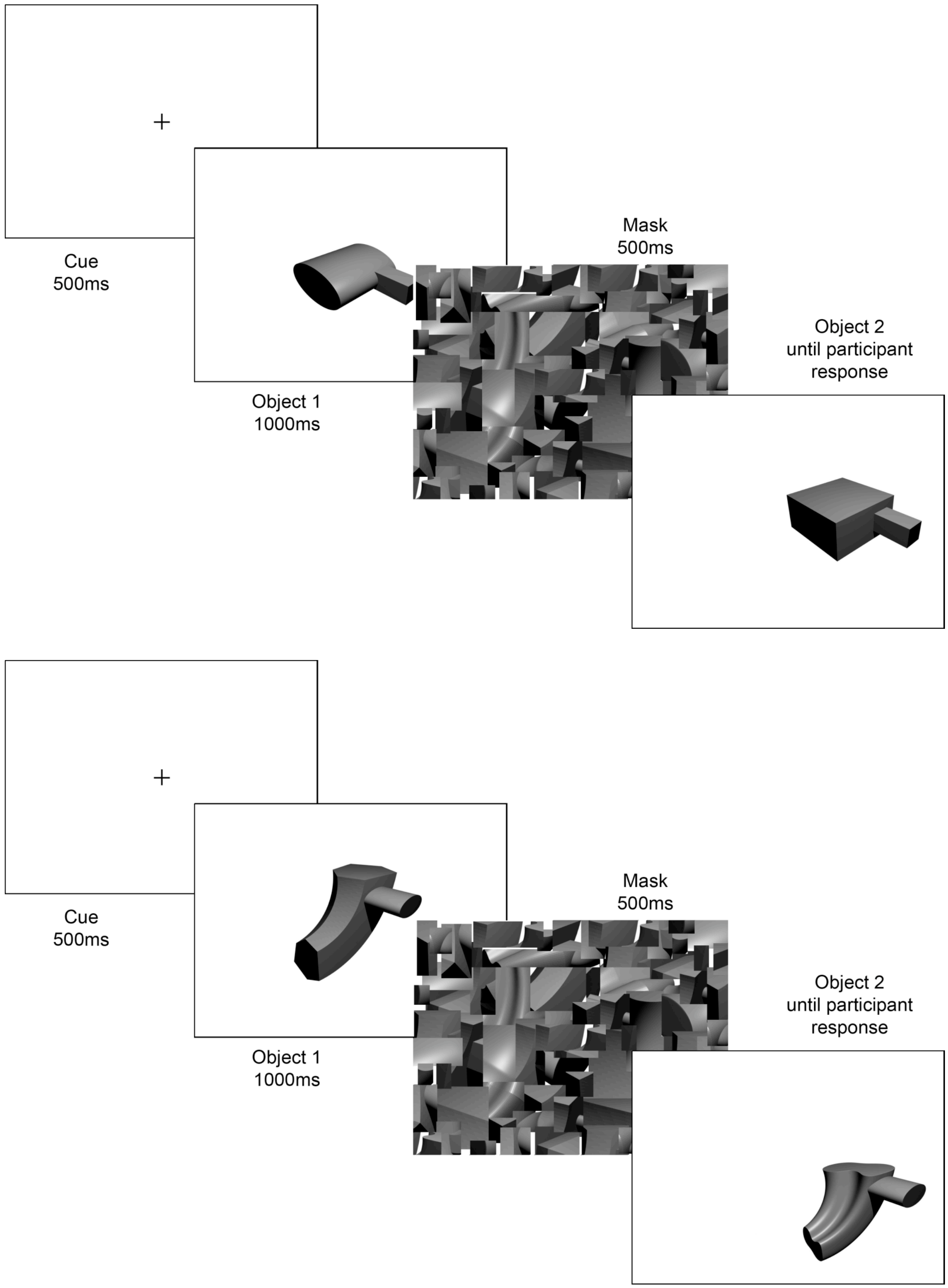


Figure 13. Examples of trials from Experiment Two, testing the edge curvature of the cross section (straight vs. curved). Both images depict “different object, different geons” (DDG) trials in which the large geon of the two-geon object changed.

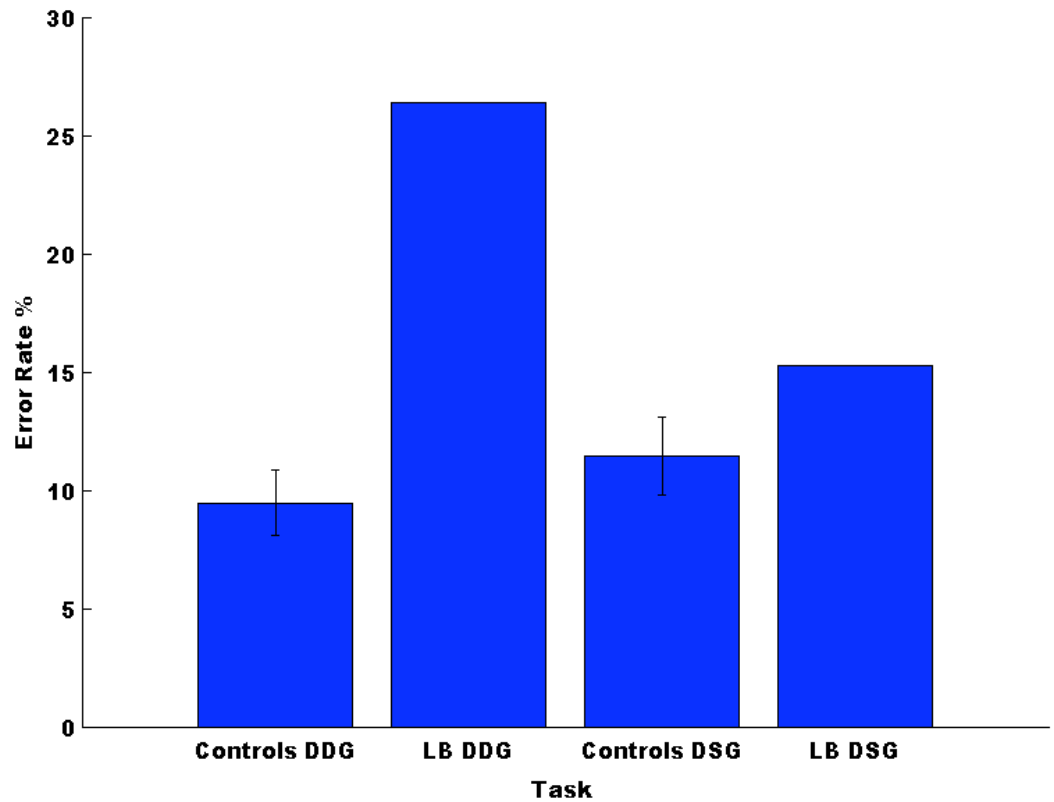


Figure 14. Mean error rates for controls and LB in Experiment 2, testing cross section curvature (straight vs. curved). DDG represents "different objects, different geons" trials, and DSG represents "different objects, same geons" trials. Error bars on the control subjects' data represent the standard error of the mean.

Just as in Experiment 1, the pattern of data in the analysis of only the large DDG trials more closely matches the pattern predicted to appear if the feature being tested defines the visual primitives used in object recognition (see Figures 6 and 7 for predicted data patterns). The data in Figure 15 do not show an interaction whereby LB is disproportionately worse than controls at within structural description discriminations (DSG trials) compared to across structural description comparisons (DDG trials), and a within subjects t-test on the mean differences between controls and LB in both conditions confirmed that there is no interaction present.

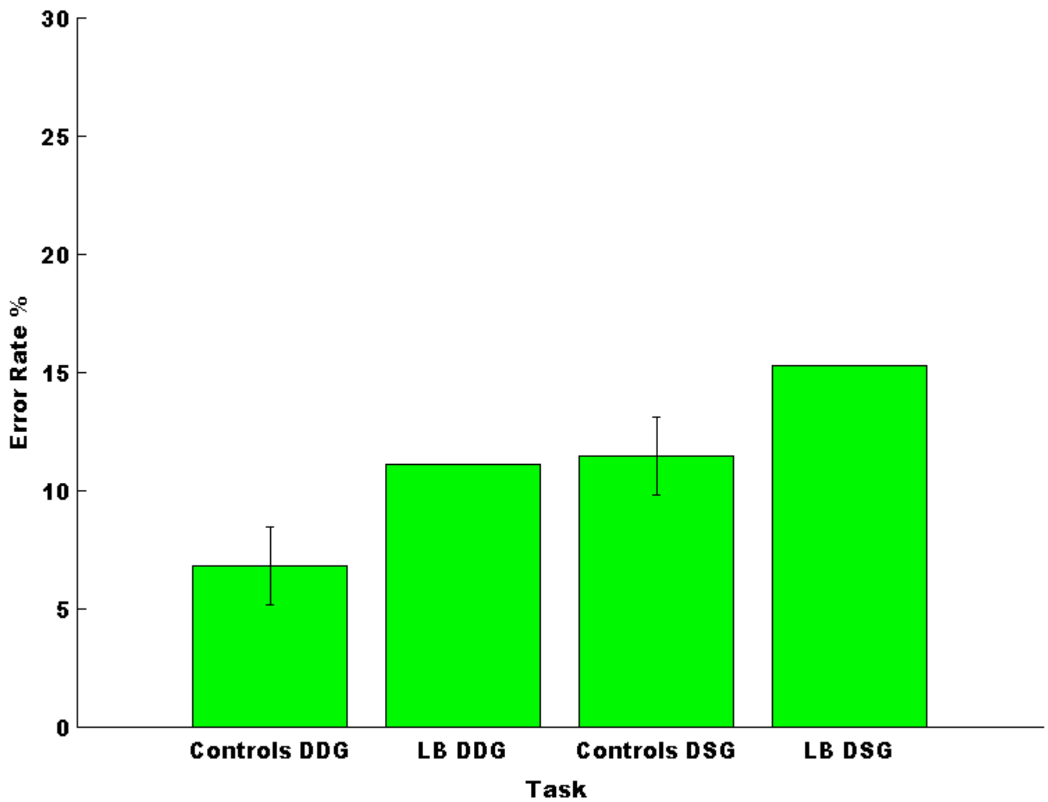


Figure 15. Mean error rates for controls and LB in Experiment 2 showing only "different object, different geons" (DDG) trials in which the larger geon changed. "Different object, same geons" (DSG) trials data are also presented.

Discussion

The results of Experiment 2 suggest that the curvature of the cross section is not a defining feature of the visual primitives used in object recognition. Even when controlling for the difficulty of the DDG trials (large geon change vs. small geon change), the pattern of data suggests that LB is not disproportionately worse at discriminating DSG trials, than she is at discriminating DDG trials relative to controls. The results of Experiment 2 presented in Figure 15 (large geon change only DDG trials) most closely match the predicted data pattern presented in Figure 7, which implies that curvature of the cross section is not a feature used to define visual primitives. A note of interest however is the overall high performance (low error rates) of LB on the DSG task in this experiment relative to all of the other experiments presented here. In each of the nine experiments presented, the DSG trials were drawn from the same pool of trials, and as a result, it was expected that controls and LB would perform consistently on DSG trials across all of the experiments (i.e., have similar reaction times and error rates). For controls, this appears to be the case for all of the experiments. For LB, this appears to be the case for all of the experiments except Experiments 2 and 8. If LB's performance on the DSG trials in Experiment 2 had been commensurate with her performance on the DSG trials of the majority of the other experiments presented here, the resulting data would suggest that the curvature of the cross section is in fact, a useful feature for defining the visual primitives used in object recognition. It is unclear why LB's performance on the DSG trials in Experiment 2 was different from her performance on DSG trials in the other experiments, but the conclusion based on these data is that edge curvature is not a feature used to define the visual primitives used in object recognition.

EXPERIMENT 3

Experiment 3 tested whether the size change along the axis (constant vs. expanding) is a defining feature of the visual primitives used in object recognition (see Figure 1).

Method

Participants

Participants in Experiment 3 (both controls and LB) were identical to those in the previous experiments reported here.

Stimuli and Materials

All materials except the visual stimuli in Experiment 3 were identical to those in Experiment 1. The stimuli used in Experiment 3 were identical to those used in Experiment 1, except that on “different object, different geons” (DDG) trials, rather than comparing objects in which the first object had a geon defined by a straight axis, and the second object had a geon defined by a curved axis (or vice versa), DDG trials compared objects in which the first object had a geon defined by an axis that maintained a constant width along its length, and the second object had a geon defined by an axis that expanded along its length (or vice versa). See Figure 16 for an example trial.

Design and Procedure

The design and procedure for Experiment 3 were the same as those of Experiment 1, except for the overall number of trials in the experiment. In Experiments 1 and 2, the features being tested were binary features, possessed by all geons (for example, all geons either have a straight or curved axis, or a straight or curved cross section). The size change of the cross section, by contrast, can assume three values (constant, expanding, and expanding & contracting) (see Figure 1). To individually test the features proposed by Biederman (1987), each possible feature was tested against all possible variations, resulting in the need for three separate experiments to test the general feature of "size change along the

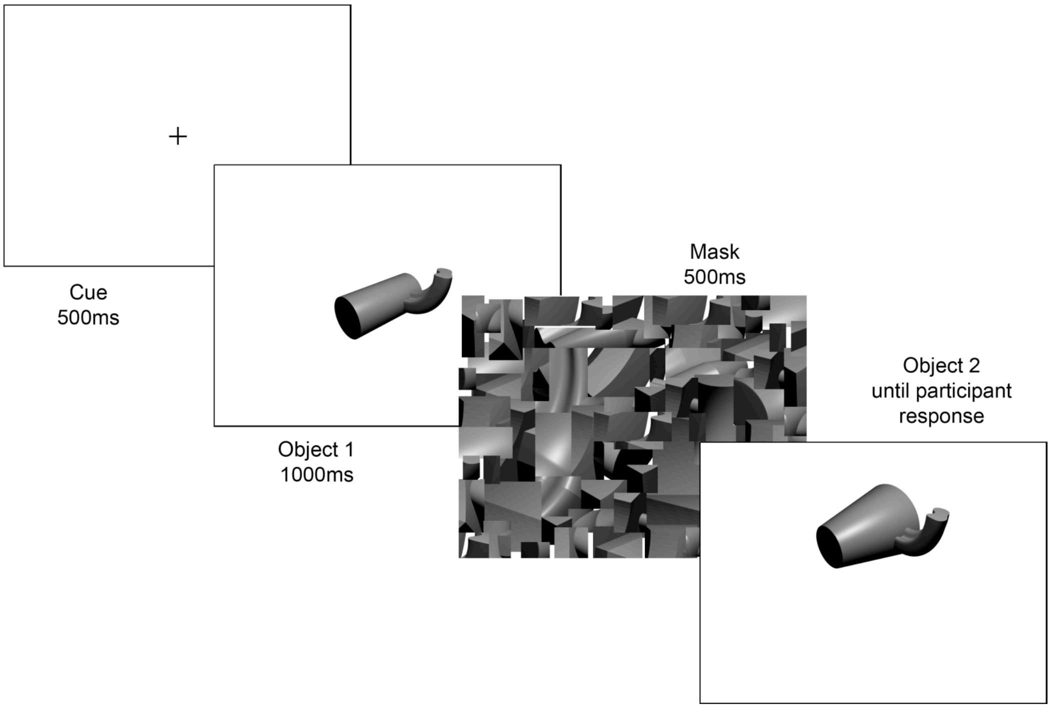


Figure 16. Example of trial sequence from Experiment 3, testing size change along the length of the axis (constant vs. expanding). In this sequence, a DDG trial is shown, in which the larger of the two geons comprising the objects has a constant axis in the first image, and an expanding axis in the second image.

axis" (one experiment to test constant vs. expanding, another to test constant vs. expanding & contracting, and another to test expanding vs. expanding & contracting). Because the size change along the axis can assume three values, and each experiment only tests two of the three values at a time against one another, only two thirds of the total number of geons, or 24 of the 36 total geons proposed by Biederman, were used in an any single experiment testing a feature that possesses three possible values. As a result, Experiments 3 through 8 have only 240 total trials, 120 of which present identical objects, and 120 of which present different objects. Of the 120 trials presenting different objects, 60 trials are “different object, same geons” (DSG) trials, and 60 are “different object, different geons” (DDG) trials. Of the 60 DDG trials, 30 trials contain changes in the position of the larger geon in the two-geon objects, and 30 trials contain changes in the position of the smaller geon.

Results

Error Data

The error data for Experiment 3 are presented in Figure 17. The data show a significant interaction of mean error rates for controls and LB between DDG and DSG trials, such that LB was disproportionately worse at the DSG trials than the DDG trials relative to controls, $t(15) = 3.04$, $p < .05$. The significant interaction in the error rates between controls and LB suggests that constant vs. expanding axis length is being used by the shape recognition system to identify visual primitives.

As in the previous experiments, the DDG trials in which only the large geon was changed were analyzed separately to account for any response patterns that may have resulted from LB’s visual field deficits (see Figure 18). A significant interaction was obtained, $t(15) = 3.33$, $p < .05$, showing that in DDG trials in which only the large geon changed, LB performed disproportionately worse at discriminating between objects that shared the same structural description (DSG trials) than she did at discriminating between objects that had different structural descriptions (DDG trials), relative to controls.

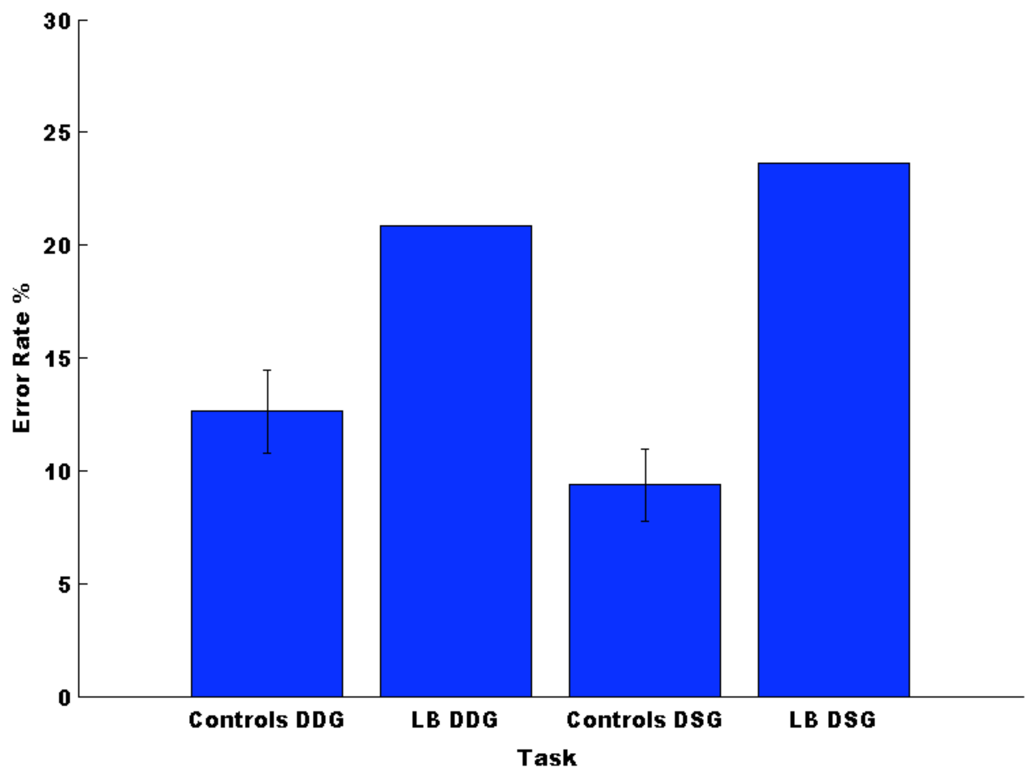


Figure 17. Mean error rates for controls and LB in Experiment 3, testing the feature of size change of the axis along its length (constant vs. expanding). DDG represents "different objects, different geons" trials, and DSG represents "different objects, same geons" trials. Error bars on the control subjects' data represent the standard error of the mean.

Discussion

The pattern of results in Experiment 3, both when including all DDG trials, and DDG trials in which only the larger of the geons changes, suggest that whether the size change of the cross section along the length of the axis is constant or expanding is a useful feature for distinguishing distinct visual primitives used in object recognition. It is interesting to note that despite the significant interaction, LB's performance was worse than the performance of controls on both DSG and DDG trials regardless of whether the data analysis included all of the DDG trials or

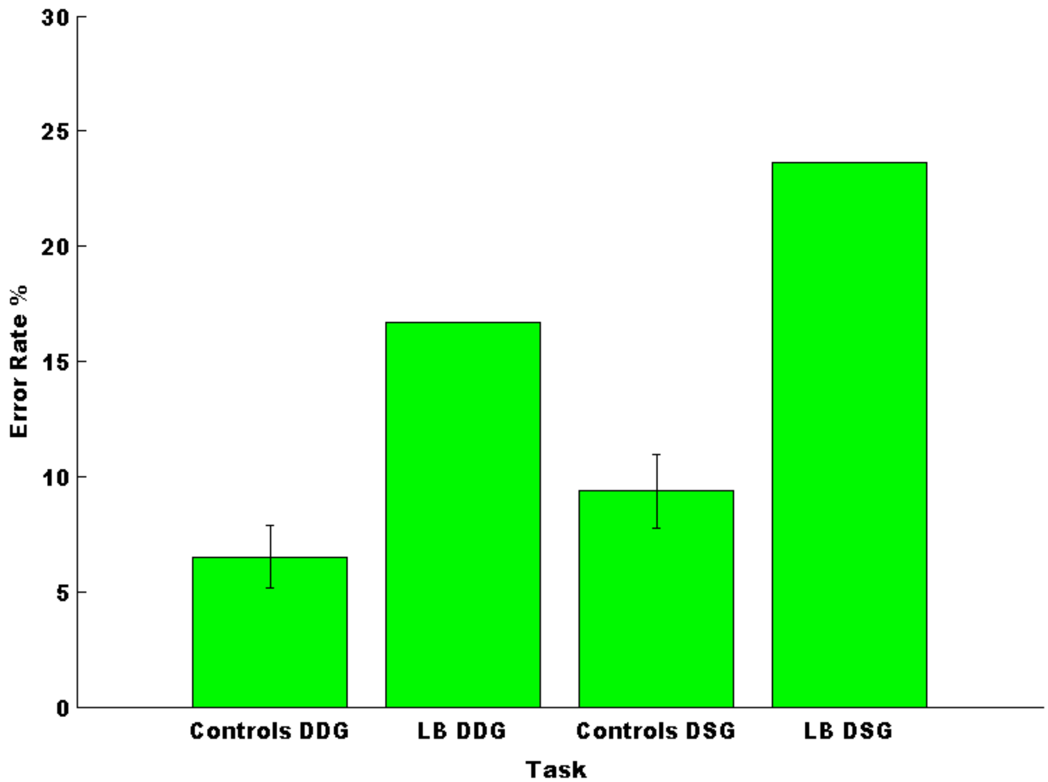


Figure 18. Mean error rates for controls and LB in Experiment 3 showing only "different object, different geons" (DDG) trials in which the larger geon changed. "Different object, same geons" (DSG) trials data are also presented. Error bars on controls' data represent standard error of the mean.

only the DDG trials in which the larger of the two geons changed. It appears to be the case that DDG discriminations between some visual primitives are more difficult for LB regardless of whether the change occurs in the position of the large or small geon in the two-geon objects. This result suggests that certain features used for discriminating visual primitives are more robustly coded by the categorical recognition system (the system that remains intact in prosopagnosic patients), perhaps because they have been more useful for object recognition throughout evolutionary history.

EXPERIMENT 4

Experiment 4 tested whether a constant vs. expanding and contracting cross section along the length of a visual primitive's axis is a feature useful for distinguishing individual visual primitives.

Method

Participants

The participants in Experiment 4 were identical to those in the previous experiments.

Stimuli and Materials

All materials in Experiment 4 were identical to those in Experiment 3. The stimuli used in Experiment 4 were the same as those used in Experiment 3, except that on DDG trials, rather than comparing objects in which one of the geons was defined by constant cross section along the length of its axis in the first object, and by an expanding cross section along the length of its axis in the second object (or vice versa), the DDG trials of Experiment 4 compared objects in which one of the geons was defined by a constant cross section along the length of its axis in the first object, and by an expanding and contracting cross section along the length of its axis in the second object (or vice versa) (see Figure 19).

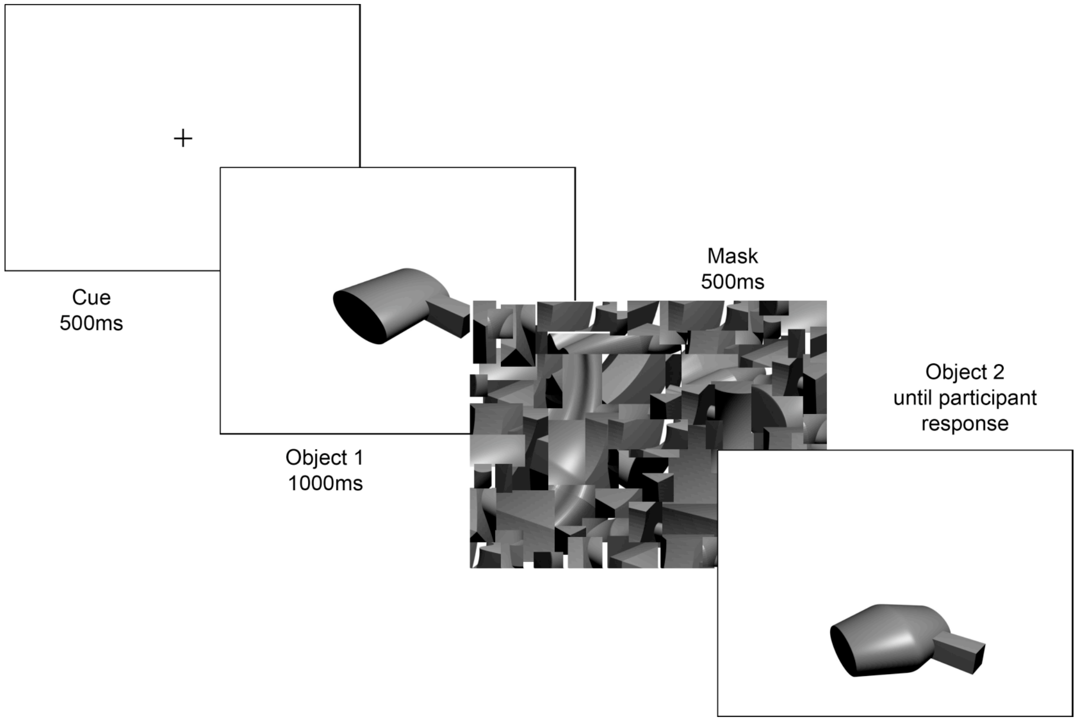


Figure 19. Example trial from Experiment 4, testing size change of the cross section along the length of the axis (constant vs. expanding & contracting). The sequence shown depicts a DDG trial in which the larger of the two geons changes from a constant cross section to an expanding and contracting cross section.

Design and Procedure

The design and procedure for Experiment 4 were identical to Experiment 3, except that on DDG trials, one of the objects' parts changed from a constant cross section to an expanding and contracting cross section, rather than from a constant cross section to an expanding cross section.

Results

Error Data

The error data for Experiment 4 are presented in Figure 20. No interaction was found between the controls' and LB's scores on the DDG and DSG trials, t(15) = 1.28, p > .05.

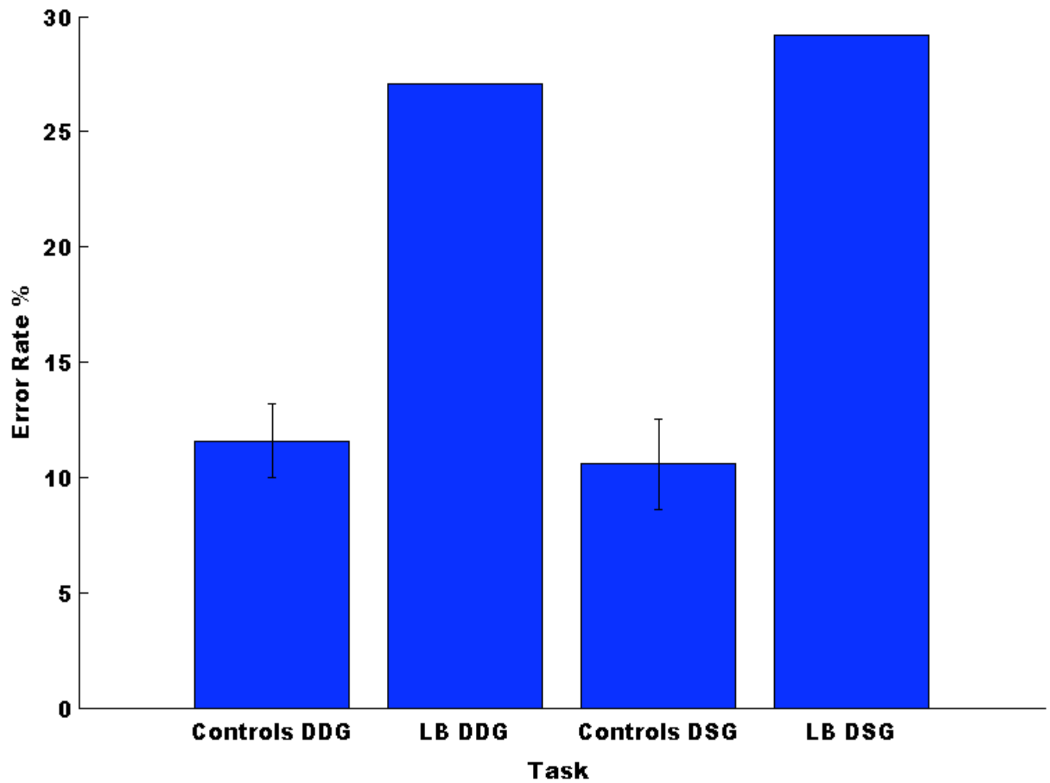


Figure 20. Mean error rates for Experiment 4, testing the feature of size change along the length of the axis (constant vs. expanding and contracting). DDG represents "different objects, different geons" trials, and DSG represents "different objects, same geons" trials. Error bars on the control subjects' data represent the standard error of the mean.

As in the previous experiments, the DDG trials in which only the larger of the two geons was changed were analyzed separately because of the possibility of LB's visual field deficits influencing her ability to accurately respond to the DDG trials in which the smaller of the two geons was changed. When including only the DDG trials in which the larger of the two geons changed, there was a significant interaction between controls' and LB's error rates on the two tasks, $t(15) = 5.45$, $p < .05$, illustrating that LB performed disproportionately poorly on DSG trials than on DDG trials, relative to controls (see Figure 21).

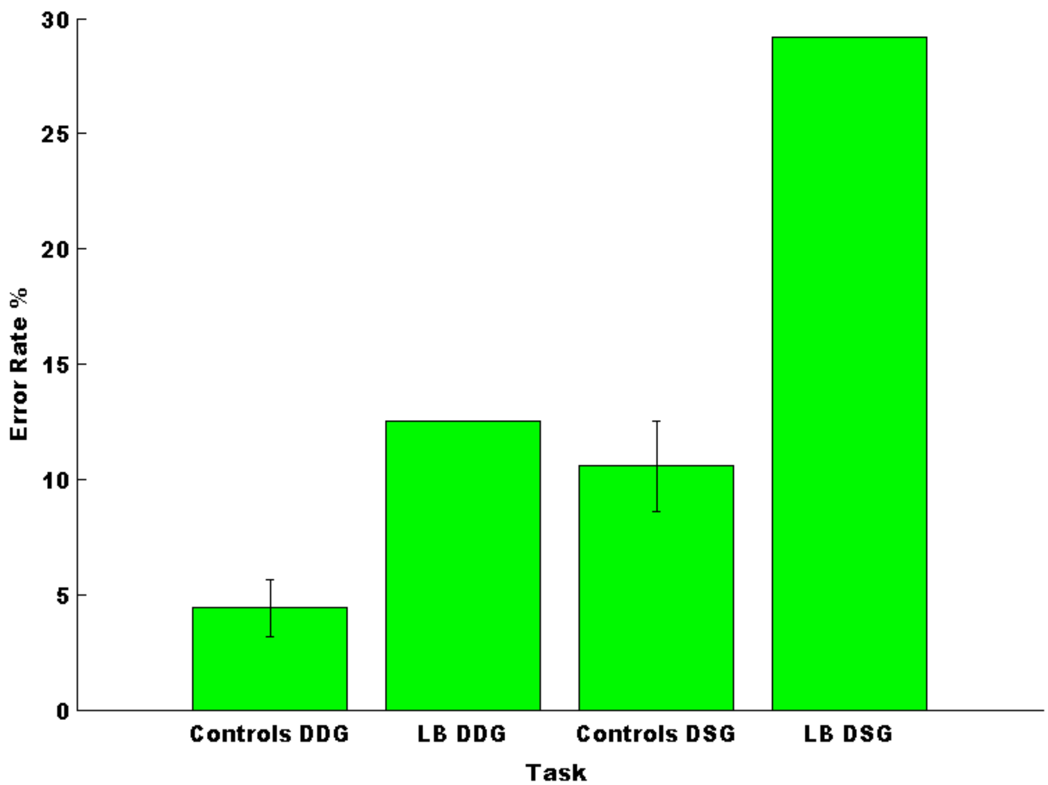


Figure 21. Mean error rates for Experiment 4 including only DDG trials in which discrimination was required among the larger of the two geons comprising the object. DDG represents "different objects, different geons" trials, and DSG represents "different objects, same geons" trials. Error bars on the control subjects' data represent the standard error of the mean.

Discussion

The results from Experiment 4 suggest that the distinction between whether the size of the cross section of a visual primitive remains constant along the length of its axis, or expands and contracts along the length of its axis is a useful distinction for defining distinct visual primitives. The predicted interaction pattern presented in Figure 6 fits the data produced by analyzing the DDG trials in which only discriminations among the larger geons were included, but does not fit the data when all DDG trials are included. If it is the case that LB's performance on the DDG trials in which discriminations must be made among the smaller of the geons is hindered by her visual field deficits, the results from Experiment 4 can be interpreted as support for the utility of a constant vs. expanding and contracting cross section as a defining feature of visual primitives. If subsequent testing however, reveals that LB's impaired performance on the DDG trials in which discriminations must be made among the smaller of the two geons is a result of something other than inadequate encoding time, the results of Experiment 4 will be more accurately interpreted as evidence against the use of constant vs. expanding and contracting cross sections as a defining feature of visual primitives.

EXPERIMENT 5

Experiment 5 once again tested the feature of size change of the cross section along the length of the axis, but here the test is addressing the utility of an expanding vs. expanding and contracting cross section as a defining feature of visual primitives.

Method

Participants

The participants in Experiment 5 were identical to those in the previous experiments.

Stimuli and Materials

The materials used in Experiment 5 were identical to those in the previous experiments. The stimuli were the same as those in the previous experiments, except that on the DDG trials, instead of discriminating among the features tested in the previous experiments, the DDG trials required discriminations between two-geon objects in which one of the geons was defined by an expanding cross section along its axis in the first object, and defined by an expanding and contracting cross section along its axis in the second object (See Figure 22).

Design and Procedure

The design and procedure of Experiment 5 were identical to those of Experiment 3.

Results

Error Data

The error data for Experiment 5 are presented in Figure 23. The data show a significant interaction of mean error rates for controls and LB between DDG and DSG trials, showing that LB was disproportionately worse at the DDG trials than the DSG trials relative to controls, $t(15) = -7.48$, $p < .05$. This interaction pattern suggests that relative to controls, LB is better at performing DSG discrimination than

DDG discriminations, a pattern opposite what would be predicted by Cooper & Wojan (2000), and Casner (2006).

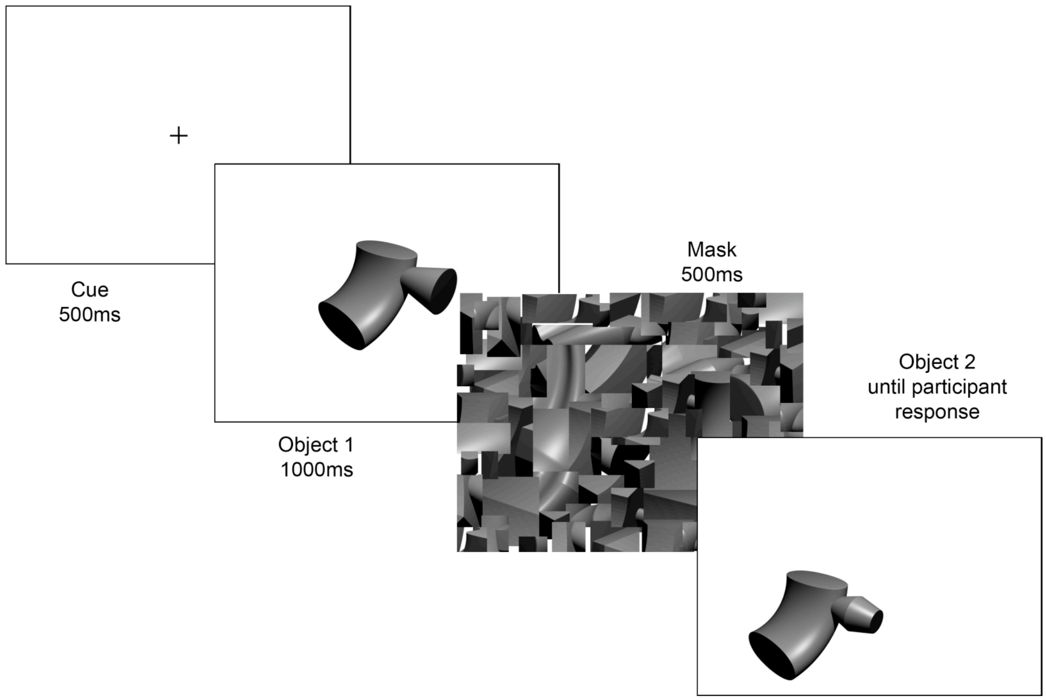


Figure 22. Sample trial from Experiment 5, testing size change of the cross section along the length of the axis (expanding vs. expanding and contracting). The shown sequence depicts a DDG trial in which the smaller of the two geons is defined by an expanding cross section in the first object, and an expanding and contracting axis in the second object.

As in the previous experiments, analyses were conducted on the DDG trials containing only large geon changes, to address data artifacts created by LB's deficient visual field. The data show a significant interaction between controls' and LB's error rates on the DDG (large geon only) and DSG trials, $t(15) = -10.66$, $p < .05$ (see Figure 24).

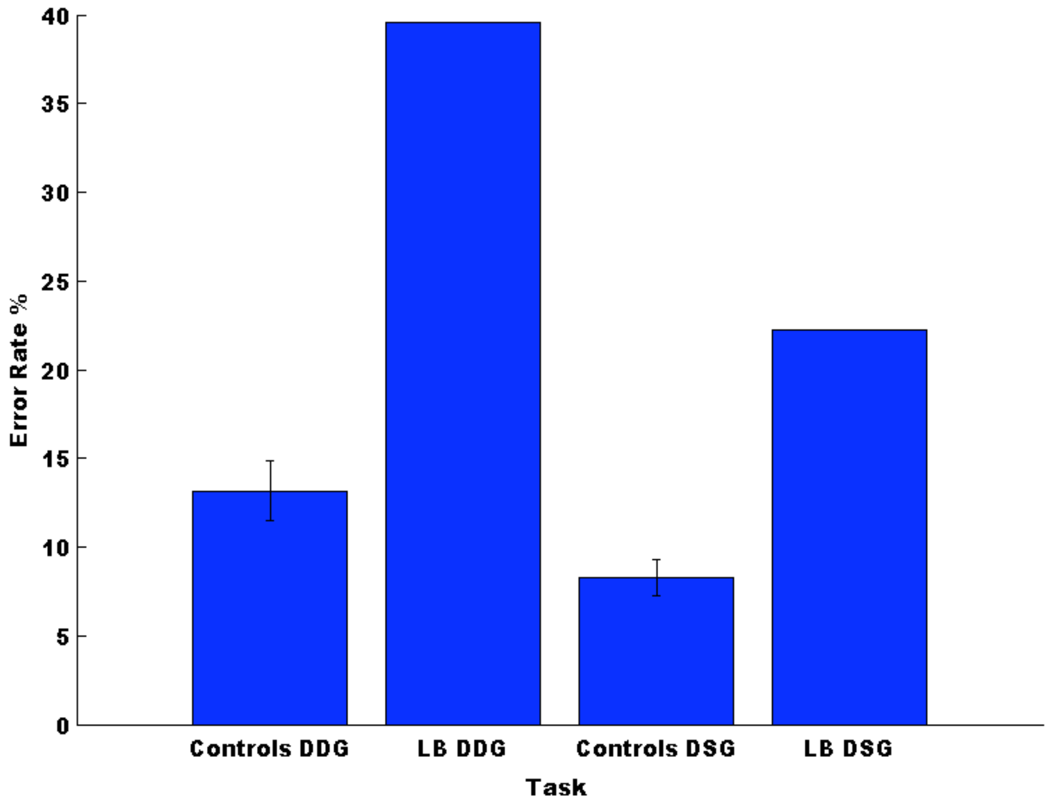


Figure 23. Mean error rates for Experiment 5, testing size change of the cross section along the length of the axis (expanding vs. expanding and contracting). DDG represents “different objects, different geons” trials, and DSG represents “different objects, same geons” trials. Error bars on the control subjects’ data represent the standard error of the mean.

Discussion

The data for Experiment 5, both when analyzed including all DDG trials and only DDG trials in which discriminations were made among the larger of the two geons, closely matches the pattern predicted in Figure 7, suggesting that whether a cross section is expanding or expanding and contracting along the length of its axis is a useless distinction for defining visual primitives used in object recognition. In fact because LB performed so poorly in the DDG trials relative to the DSG trials,

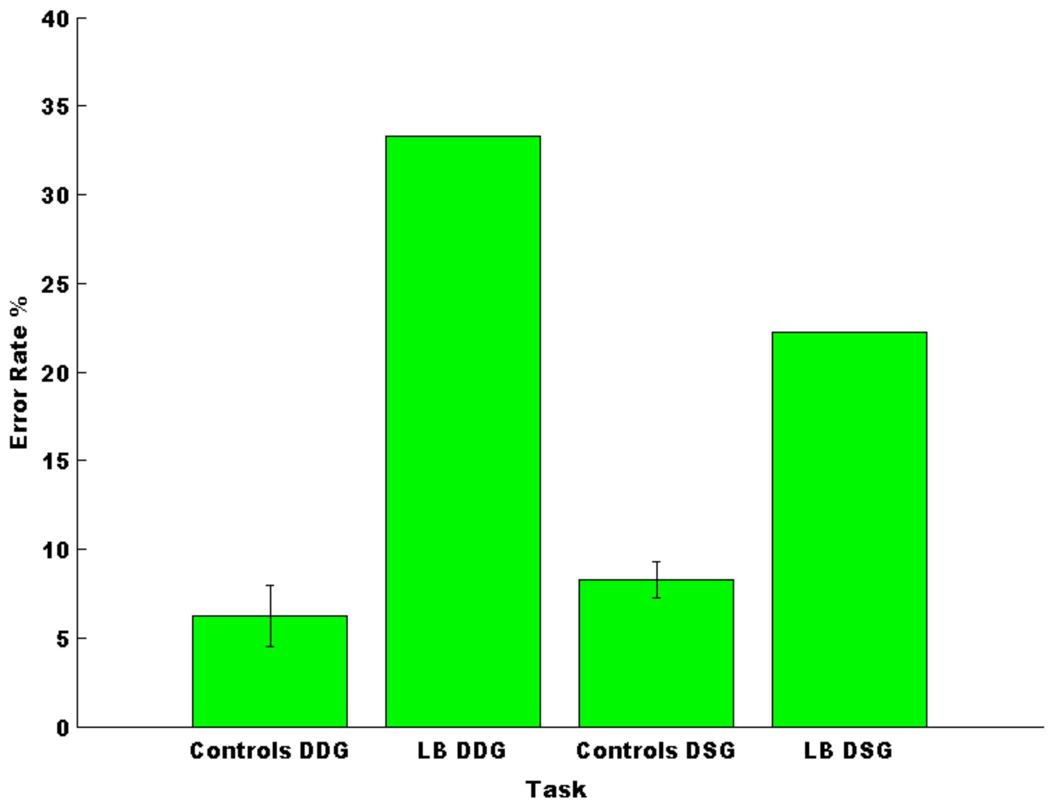


Figure 24. Mean error rates for Experiment 5, including DDG trials in which discriminations were made among only the larger of the two geons. DDG represents "different objects, different geons" trials, and DSG represents "different objects, same geons" trials. Error bars on the control subjects' data represent the standard error of the mean.

even when controlling for the size of the geon that changed in the DDG trials, it seems logical to conclude that she found the objects in the DDG trials to be less similar to one another than the objects in the DSG trials. The conclusion from these results is that the shape recognition system does not differentially code visual primitives defined by expanding vs. expanding and contracting cross sections. In terms of everyday objects, this implies that when an observer is discriminating between two one-part objects that might be described as a football and a cone, the observer must make use of his or her coordinate recognition system because the defining features of the two shapes are not differentiated by the shape recognition system, and as a result, the categorical recognition system cannot be used to discriminate between the two objects.

EXPERIMENT 6

Experiment 6 tested whether cross section symmetry (reflectional vs. reflectional and rotational) is a feature used by the shape recognition system for discriminating between visual primitives.

Method

Participants

The participants in Experiment 6 were identical to those in the previous experiments.

Stimuli and Materials

All materials used in Experiment 6 were identical to those used in the previous experiments. The visual stimuli used in Experiment 6 were the same as those used in the previous experiments, except that on the DDG trials, participants discriminated between two-geon objects in which a geon defined by a reflectionally symmetrical cross section in the first object was replaced by a geon defined by a reflectionally and rotationally symmetrical cross section in the second object (see Figure 25).

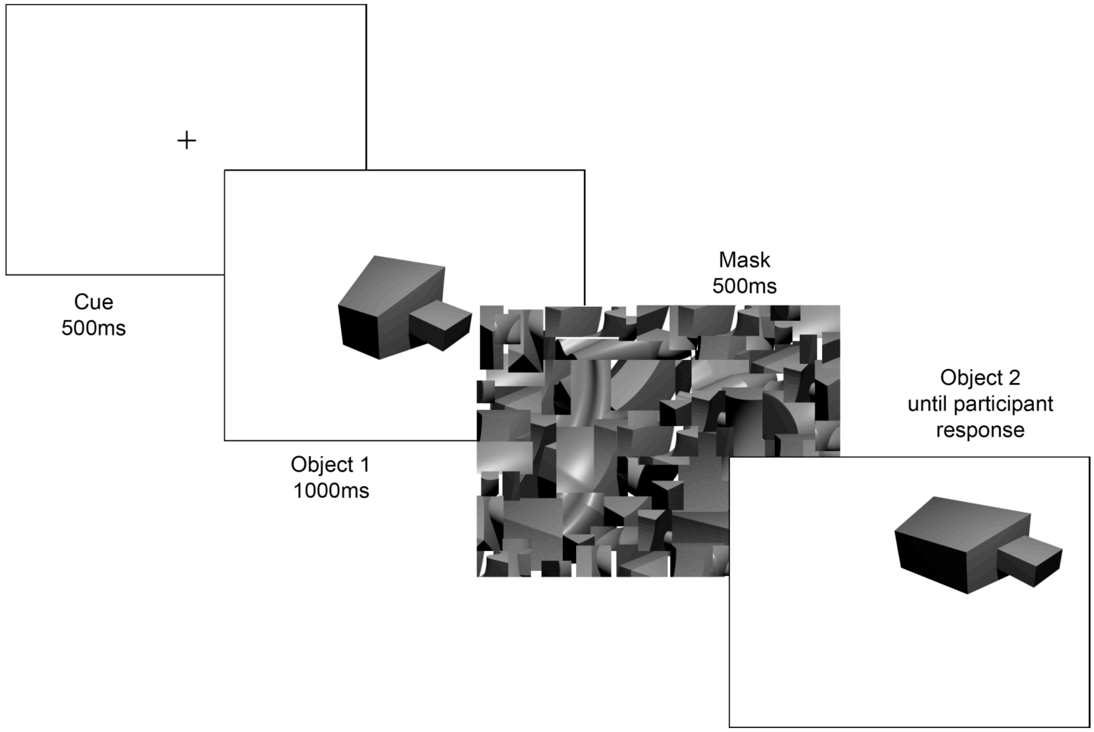


Figure 25. Example trial from Experiment 6, testing cross section symmetry (reflectional and rotational vs. reflectional). The sequence shown illustrates a DDG trial in which the larger of the two geons is defined by a reflectionally and rotationally symmetrical cross section in the first object, and a reflectionally symmetrical cross section in the second object.

Design and Procedure

The design and procedure of Experiment 6 were identical to those of Experiment 3.

Results

Error Data

Mean error rates for Experiment 6 are shown in Figure 26. The error rate data illustrate a significant interaction between controls' and LB's performance on DDG and DSG trials, where relative to controls, LB was disproportionately worse at within structural description discriminations (DSG trials) than between structural description discriminations (DDG trials), $t(15) = 2.31$, $p < .05$.

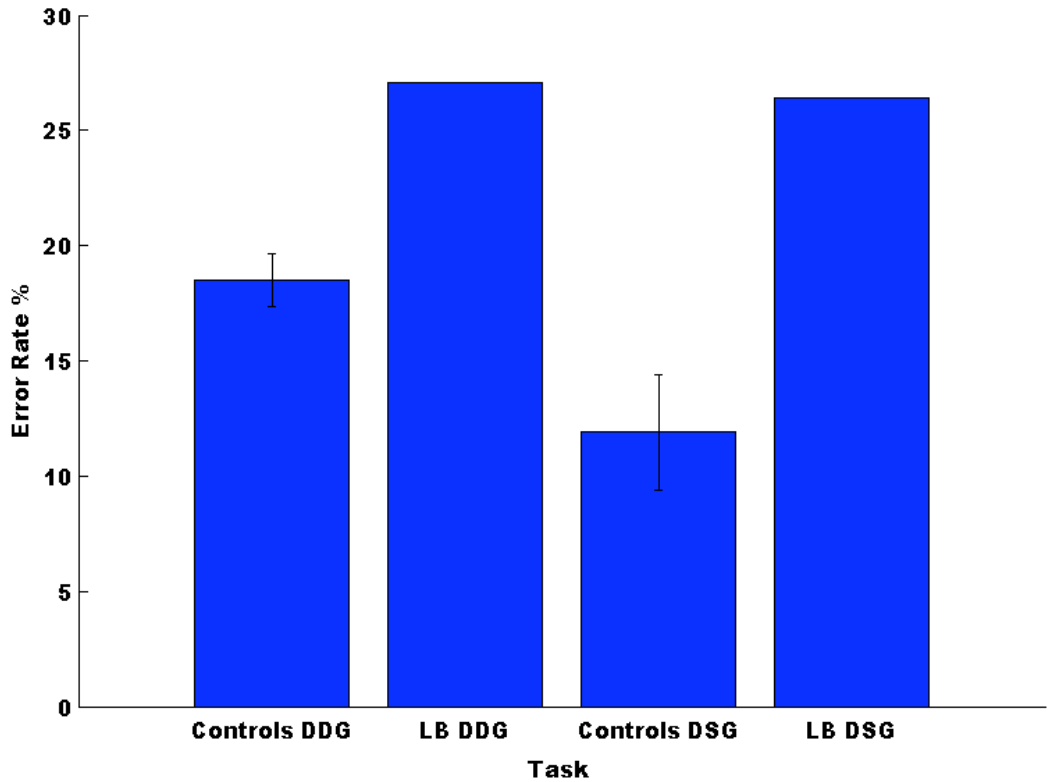


Figure 26. Mean error rates for Experiment 6, testing symmetry of the cross section (reflectional vs. reflectional and rotational). DDG represents “different objects, different geons” trials, and DSG represents “different objects, same geons” trials. Error bars on the control subjects’ data represent the standard error of the mean.

As in the previous experiments, the data were also analyzed with the DDG trials in which the geon change only occurred in the position of the large geon. The results of this analysis are presented in Figure 27. In DDG trials in which only the large geon changed, a significant interaction was revealed between controls’ and LB’s error rates, suggesting that compared to controls, LB performed disproportionately worse on the DSG trials than on the DDG trials, $t(15) = 12.09$, $p < .05$.

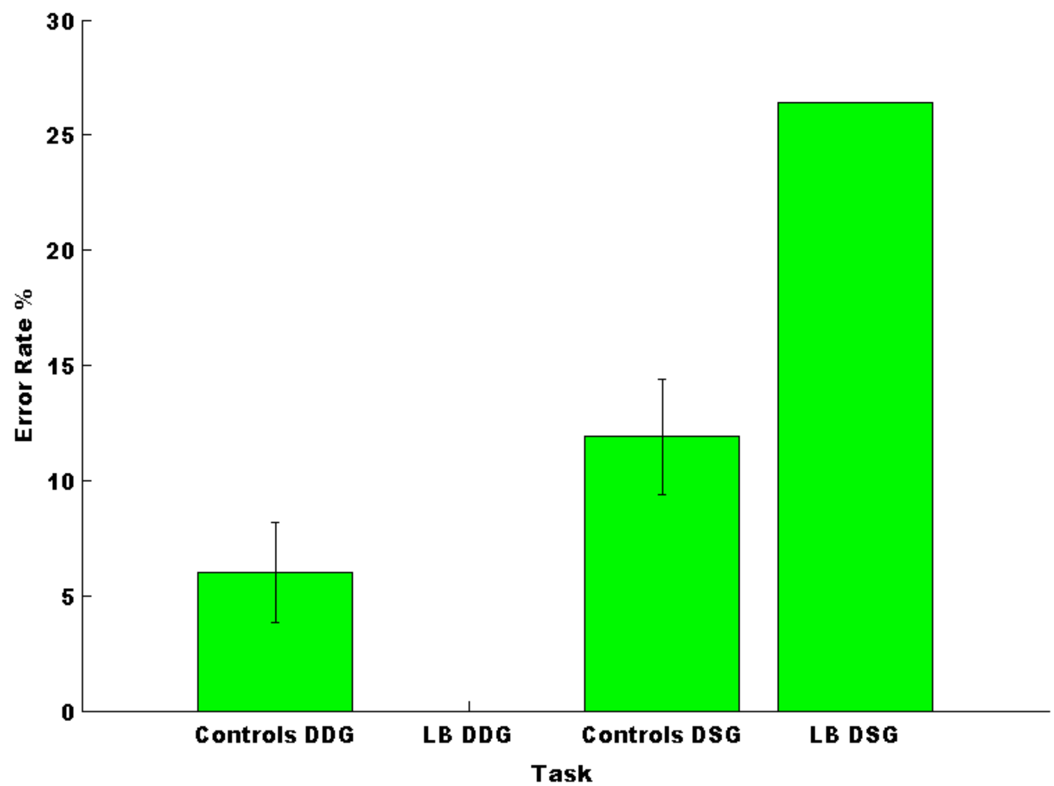


Figure 27. Mean error rates for Experiment 6, including only DDG trials in which the larger of the geons changed. DDG represents "different objects, different geons" trials, and DSG represents "different objects, same geons" trials. Error bars on the control subjects' data represent the standard error of the mean.

Discussion

The interaction between the error rates of controls and LB suggests that the distinction of a reflectionally symmetrical or reflectionally and rotationally symmetrical cross section is used to define the visual primitives used in object recognition. Despite the fact that LB's error rates are very similar for the DDG and DSG trials (Figure 26), controls' error rates are unusually high for the DDG trials, suggesting that the DDG trials in this experiment are particularly difficult. This possibility seems even more plausible when inspecting the data in Figure 27, which includes only the DDG trials in which participants discriminate among the larger of the two geons composing the objects. The significant interactions illustrated in Figures 26 and 27 occur in the same direction, but in Figure 27, which represents only the large geon DDG trials, the interaction becomes more pronounced, and more closely matches the pattern shown in Figure 6, indicating that the symmetry of the cross section (reflectional vs. rotational and reflectional) is used to define the primitives used for object recognition.

EXPERIMENT 7

Experiment 7 tested whether identifying the symmetry of the cross section of a visual primitive as either reflectional and rotational or asymmetrical is a feature used by the shape recognition system to represent distinct visual primitives.

Method

Participants

The participants in Experiment 7 were identical to those in the previous experiments.

Stimuli and Materials

All materials used in Experiment 7 were identical to those used in the previous experiments. The stimuli used in Experiment 7 were the same as those used in the previous experiments, except that on the DDG trials, participants discriminated between two-geon objects in which a geon defined by a reflectionally and rotationally symmetrical cross section in the first object was replaced by a geon defined by an asymmetrical cross section in the second object (see Figure 28).

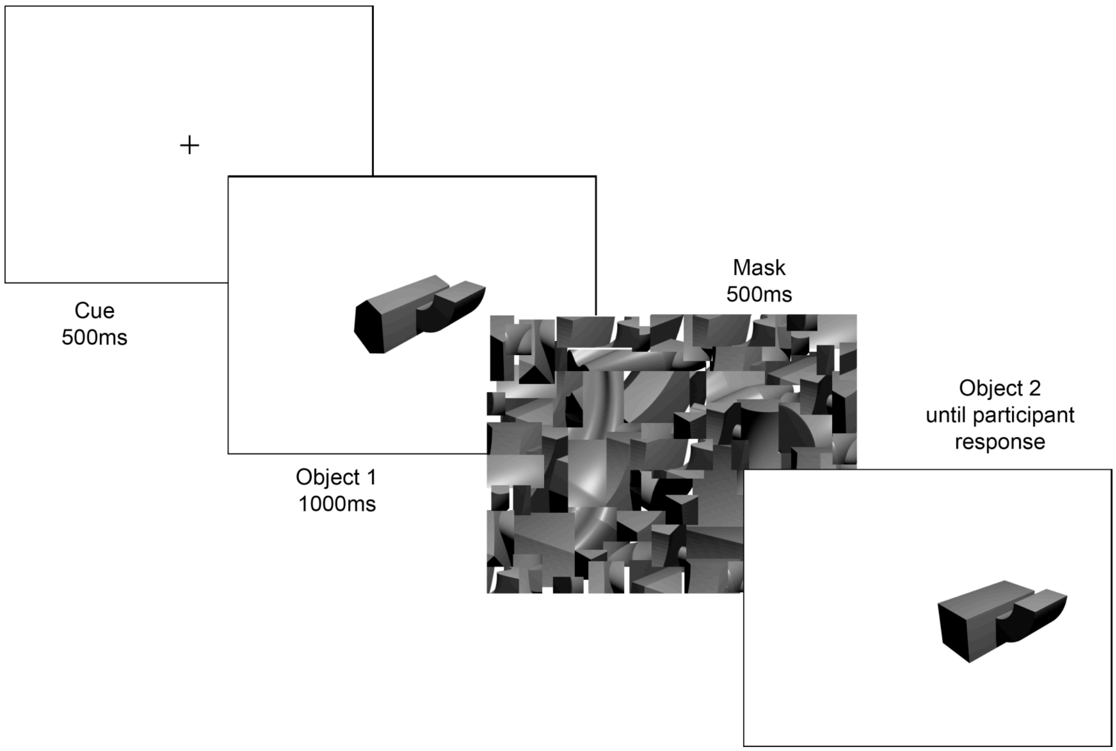


Figure 28. Example trial from Experiment 7, testing cross section symmetry (reflectional and rotational vs. asymmetrical). The sequence shown illustrates a DDG trial in which the large geon is defined by an asymmetrical cross section in the first object, and is replaced by a geon defined by a reflectionally and rotationally symmetrical cross section in the second object.

Design and Procedure

The design and procedure of Experiment 7 are identical to those of Experiment 3.

Results

Error Data

Error rate data for Experiment 7 are presented in Figure 29. The data show a significant type of Task x Participant interaction, in which LB's performance is disproportionately worse on DSG trials than on DDG trials relative to controls, $t(15) = 5.87$, $p < .05$.

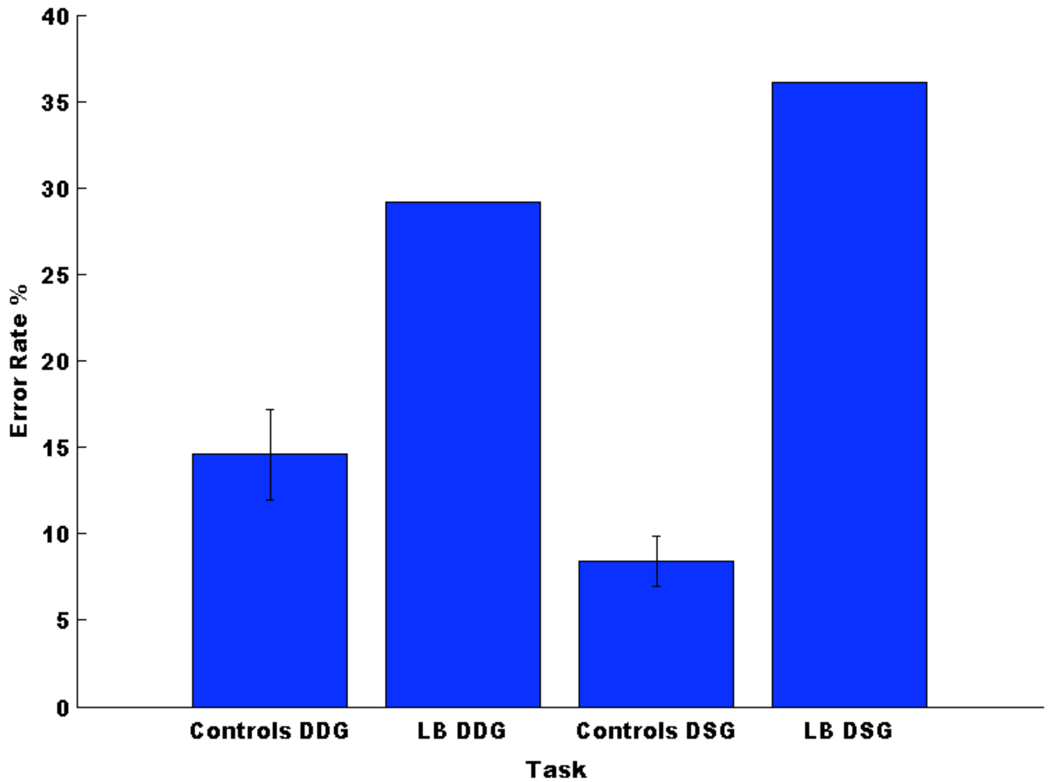


Figure 29. Mean error rates for Experiment 7, testing cross section symmetry (reflectional and rotational vs. asymmetrical). DDG represents "different objects, different geons" trials, and DSG represents "different objects, same geons" trials. Error bars on the control subjects' data represent the standard error of the mean.

As in the previous experiments, DDG trials in which only the large geon change were analyzed separately to address the possibility that LB's DDG error rates are being artificially inflated by her inability to properly encode the small geon of the first object presented in each trial due to time constraints. The Task x Participant interaction became even more apparent in these data, $t(15) = 12.65$, $p < .05$, suggesting that when given enough time to properly encode the geons on the

DDG trials, LB performs much worse on DSG trials than on DDG trials relative to controls (see Figure 30).

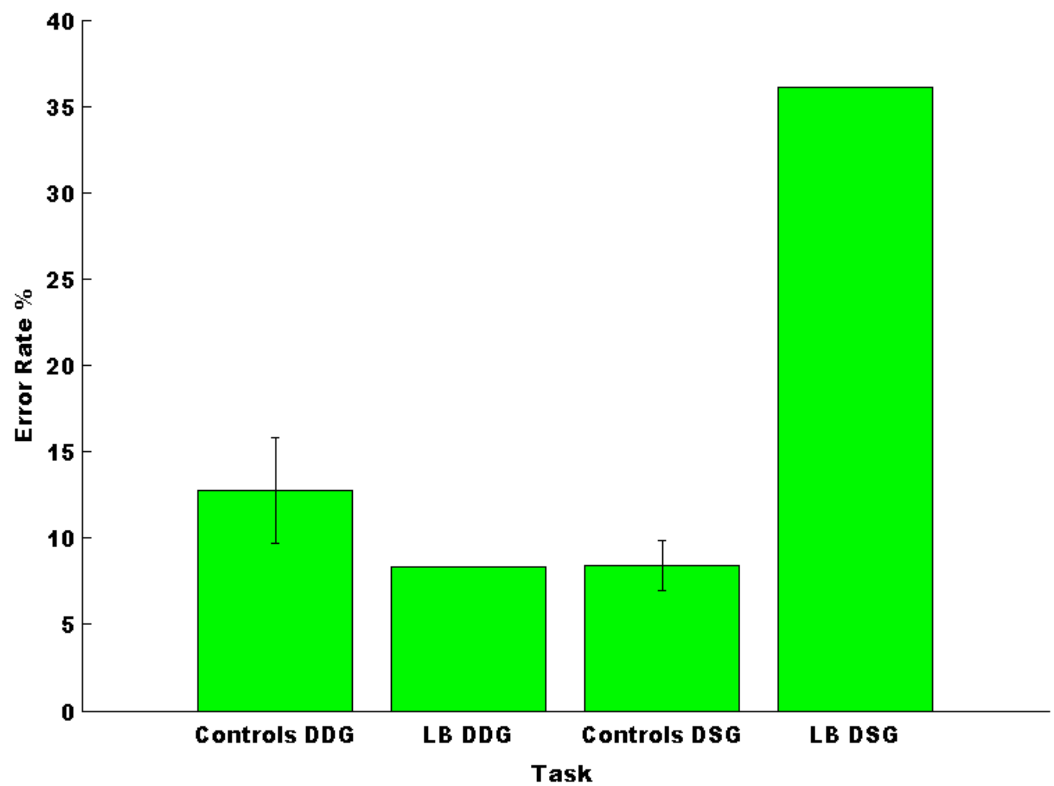


Figure 30. Mean error rates for Experiment 7, testing cross section symmetry (reflectional & rotational vs. asymmetrical), including only DDG trials in which the larger of the geons changed. DDG represents “different objects, different geons” trials, and DSG represents “different objects, same geons” trials. Error bars on the control subjects’ data represent the standard error of the mean.

Discussion

The pattern of results in Experiment 7 suggest that defining the symmetry of the cross section of a visual primitive as either reflectional and rotational or as asymmetrical is a useful distinction for classifying visual primitives as distinct from one another. Because LB showed greater deficits relative to controls when discriminating DSG trials than when discriminating DDG trials, regardless of whether all of the DDG trials were included, or just the DDG trials in which only the large geon changed, the data clearly suggest that reflectional and rotational vs. asymmetrical cross section symmetry is a feature used by the shape recognition system for classifying distinct visual primitives. This pattern is particularly clear in Figure 30, which closely resembles the hypothetical data presented in Figure 6, illustrating the predicted pattern of results expected when a feature used by the shape recognition system to classify visual primitives.

EXPERIMENT 8

Experiment 8 tested whether reflectional vs. asymmetrical symmetry of the cross section is a feature useful for distinguishing visual primitives.

Method

Participants

The participants in Experiment 8 were identical to those in all of the previous experiments.

Stimuli and Materials

All materials in Experiment 8 were identical to those in the previous experiments. The stimuli in Experiment 8 were the same as those used in the previous experiments, except that on the DDG trials, participants discriminated between two-geon objects in which a geon defined by a reflectionally symmetrical cross section in the first object was replaced by a geon defined by an asymmetrical cross section in the second object (see Figure 31).

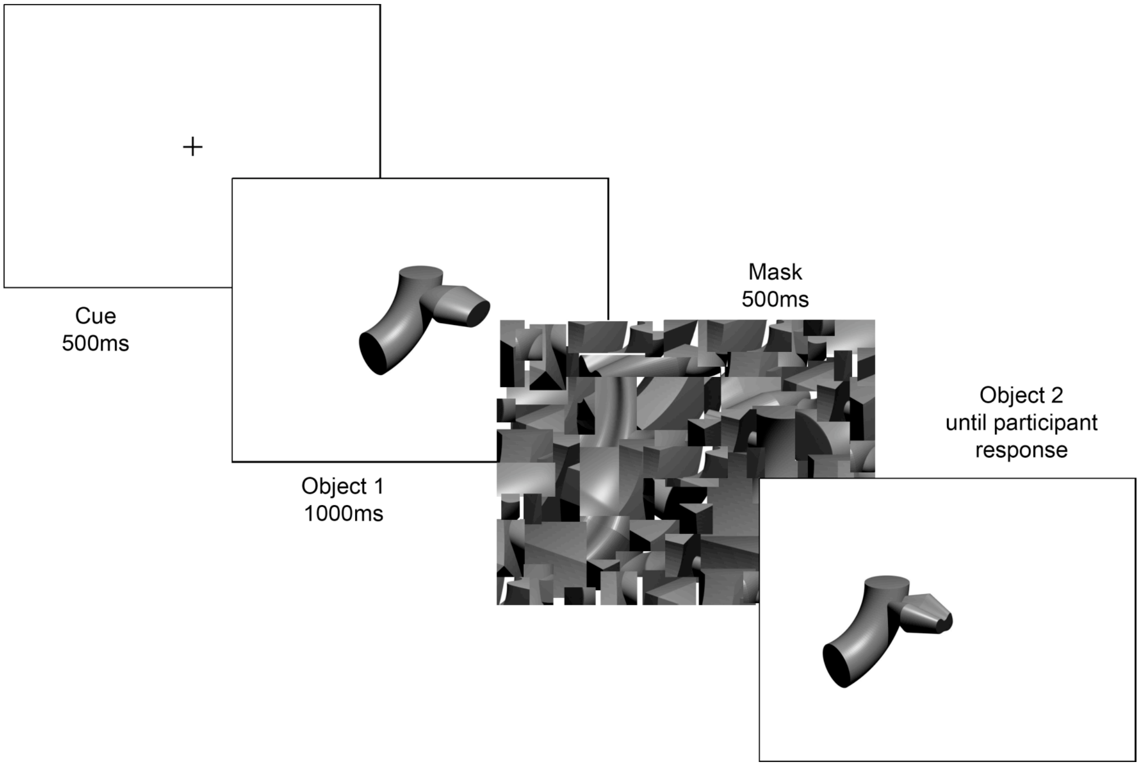


Figure 31. Example trial from Experiment 8, testing cross section symmetry (reflectional vs. asymmetrical). The sequence shown illustrates a DDG trial in which the small geon defined by a reflectional cross section in the first object, is replaced by a small geon defined by an asymmetrical cross section in the second object.

Design and Procedure

The design and procedure of Experiment 8 were identical to those of Experiment 3.

Results

Error Data

Error data for Experiment 8 are shown in Figure 32. The Task x Participant interaction was significant, $t(15) = 21.42$, $p < .05$, showing that LB was disproportionately worse at the DSG trials than the DDG trials relative to controls.

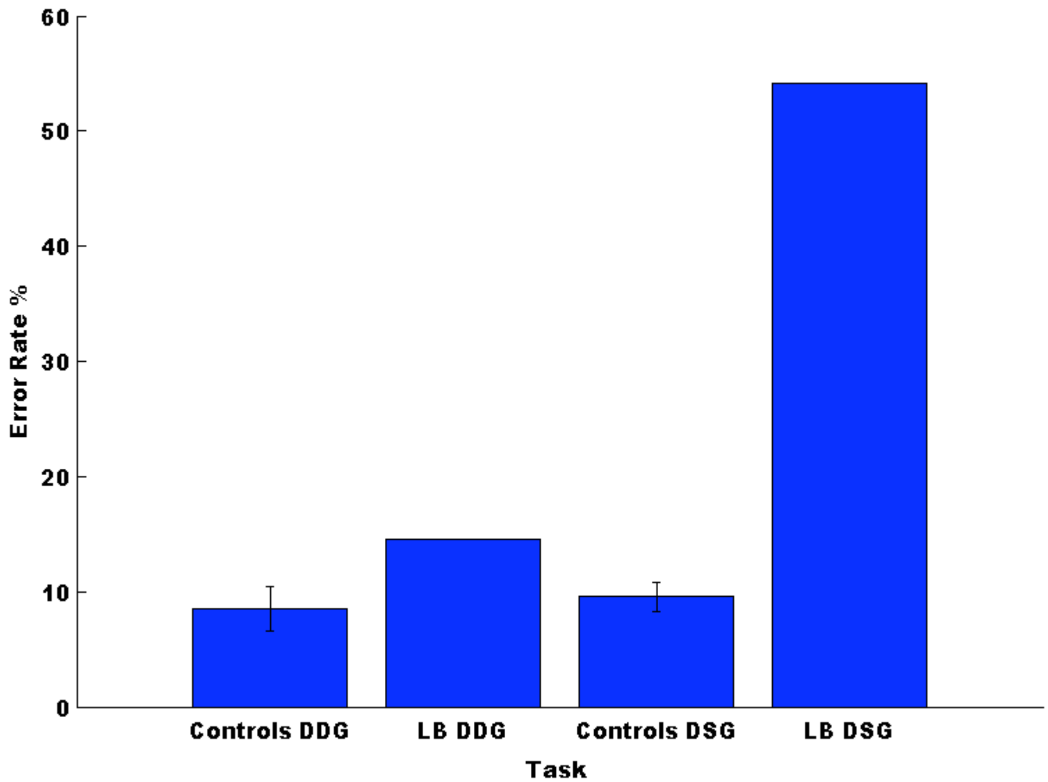


Figure 32. Mean error rates for Experiment 8, testing the feature of cross section symmetry (reflectional vs. asymmetrical). DDG represents "different objects, different geons" trials, and DSG represents "different objects, same geons" trials. Error bars on the control subjects' data represent the standard error of the mean.

As in the previous experiments, the DDG trials in which only the larger of the geons changed were analyzed separately. A significant interaction was present in the data, $t(15) = 27.42$, $p < .05$, showing that was LB was worse at DSG trials than at DDG trials relative to the controls (see Figure 33).

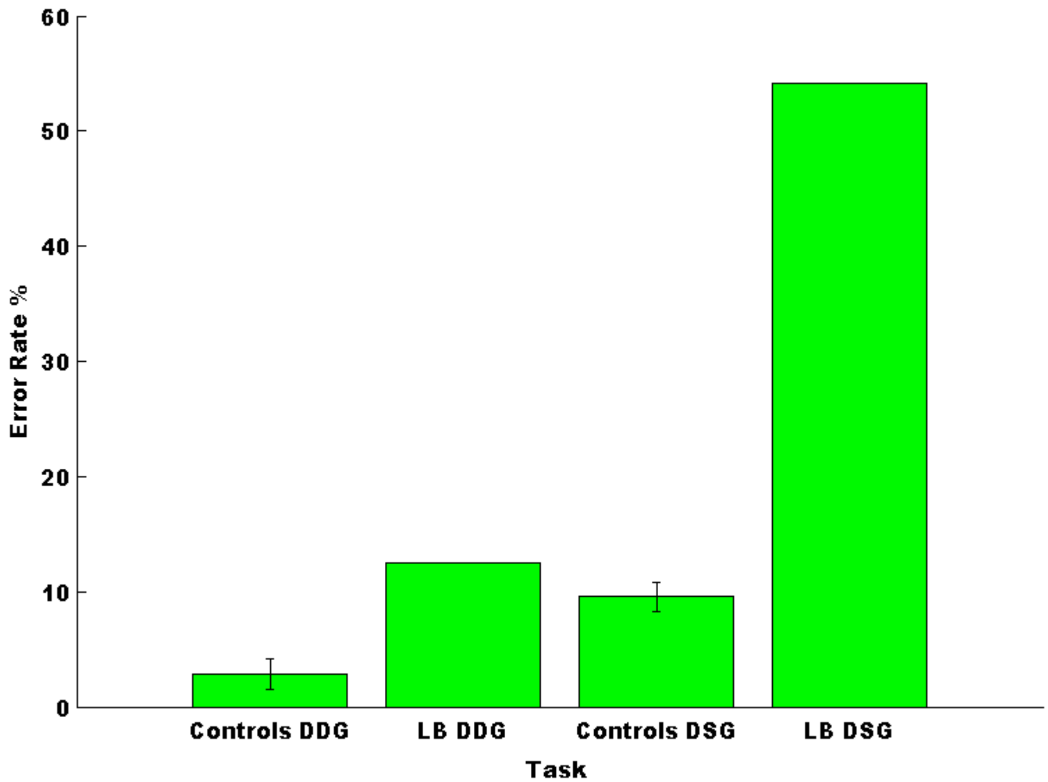


Figure 33. Mean error rates for Experiment 8, testing cross section symmetry (reflectional vs. asymmetrical), including only DDG trials in which discriminations occurred to only the larger of the two geons. DDG represents “different objects, different geons” trials, and DSG represents “different objects, same geons” trials. Error bars on the control subjects’ data represent the standard error of the mean.

Discussion

The results of Experiment 8 provide strong evidence that the property of cross section symmetry (reflectional vs. asymmetrical) is a feature used by the shape recognition system to classify visual primitives. The interaction pattern present both when all DDG trials are included (Figure 32), and when the large geon only DDG trials are included (Figure 33), closely matches the predictions shown in Figure 6, indicating that the feature being tested is in fact used by the shape recognition system to identify visual primitives. LB's performance on the DDG trials in this experiment was quite good, even before controlling for the difficulty of the DDG trials (by looking at only the large change DDG trials). Conversely, LB's performance on the DSG trials was considerably poorer than her performance on the DSG trials in the other experiments, which is puzzling. Recall that in Experiment 2, LB's performance on the DSG trials was considerably better than her DSG performance in the other experiments (see Figure 14). LB's abnormal performance on the DSG trials in Experiments 2 and 8 are difficult to explain given the fact that the DSG trials in all of the experiments were identical, and the prediction is that the performance of the controls and LB on DSG trials, regardless of the particular experiment, should have remained relatively constant. Performance of controls on DSG trials was fairly constant across experiments. This pattern suggests that there was nothing abnormal about the presentation of the DSG trials in Experiments 2 or 8 for controls or LB. Despite this anomaly, even if LB's performance on the DSG trials had been commensurate with her performance on the DSG trials of the other experiments, it is very likely that the same interaction pattern would have emerged in the data, showing that LB was disproportionately worse at discriminating objects in the DSG trials than in the DDG trials.

The overall conclusion from Experiment 8 then is that whether the cross section is of a visual primitive is reflectionally symmetrical or asymmetrical is a feature used by the shape recognition system for classifying visual primitives.

EXPERIMENT 9

A ninth experiment was added to the original eight to test the possibility that LB's relatively poor performance on the all-geon DDG trials was a result of incomplete coding of the smaller of the two geons during the presentation of the initially presented image on each trial (see Experiment 1 Discussion for review). To test this possibility, Experiment 9 replicated Experiment 7 with the exception that the initially presented object remained on the screen for 4000 ms rather than 1000 ms. This manipulation was devised based on feedback from LB, who suggested that when presented for only 1000 ms, she did not have enough time to scan the first object and effectively encode both parts (which disproportionately hindered encoding of the smaller of the two geons) (see Experiment 1 Discussion for explanation). Experiment 7 was chosen for replication because of the large differences between LB's performance on the all-geon DDG trials (when changes occurred in the position of the large geon or small geon), and large-geon only DDG trials (see Figures 29 and 30). If by adding additional time to the presentation of the initially presented object, LB's performance on the all-geon DDG trials improved, while her performance on the large-geon DDG trials remained roughly the same, Experiment 9 will have provided support to the hypothesis that LB's performance on the DDG trials was being influenced by encoding difficulties resulting from her deficient visual field.

Method

Participants

Only patient LB participated in Experiment 9.

Stimuli and Materials

All materials in Experiment 9 were identical to those in the previous experiments. Visual stimuli used in Experiment 9 were identical to those used in Experiment 7 (see Figure 27).

Design and Procedure

The design and procedure of Experiment 9 were the same as those of Experiment 7, except that rather than being presented for 1000 ms, the initial image of presentation remained on the screen for 4000 ms before being masked.

Results

Error Data

The error data for Experiment 9 are presented in Figure 34.

Discussion

The results of Experiment 9 suggest that had LB been provided with additional time to fully scan and encode the initially presented image in each of the experiments, that there would have been no need to separately analyze her performance on the DDG trials to account for task difficulty. Although her performance on the large geon DDG trials was better than her performance on the combined large and small DDG trials in Experiment 9, the difference was not as dramatic as the difference between her performance on the all-geon DDG, and large-geon only DDG trials in Experiments 1 through 8. The results of Experiment 9 suggest that the overall conclusions about whether a property is coded or not should be based on only the large geon DDG trials in Experiments 1 through 8.

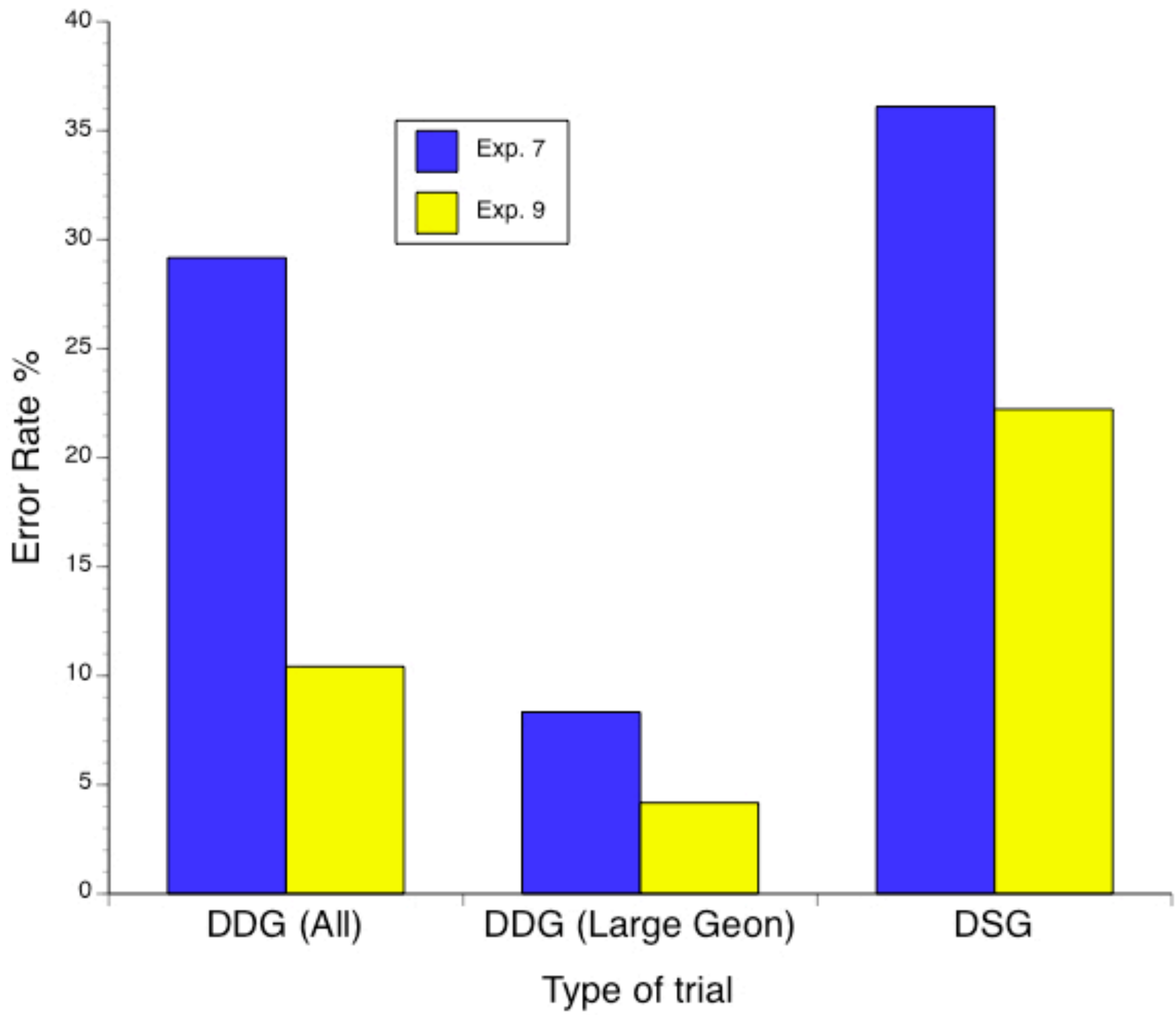


Figure 34. Mean error rates for LB from Experiments 7 and 9. In experiment 7, the initial image of presentation was present for only 1000 ms, whereas in Experiment 9, the initial image of presentation remained on the screen for 4000 ms.

GENERAL DISCUSSION

The purpose of the research presented here was to empirically determine the visual primitives used for basic level object recognition, by comparing the abilities of a prosopagnosic patient to those of controls at discriminating among objects composed of visual primitives defined by Biederman (1987). Biederman proposed a set of features used to define the visual primitives used in object recognition, and based on every combination of his features, he concluded that there exist 36 visual primitives, referred to as geons, that are used for all basic level object recognition tasks. By systematically testing each variation of each feature independently, the results of the current studies indicate which of Biederman's geons are actually coded as distinct visual primitives by the object recognition system.

The results of the first eight experiments presented here are summarized in Table 2.

Experiment	Property Tested	Used to define visual primitives used in object recognition?
1	Axis curvature (straight vs. curved)	Yes
2	Curvature of the cross section (straight vs. curved)	No
3	Size change of the cross section along the axis (constant vs. expanding)	Yes
4	Size change of the cross section along the axis (constant vs. expanding & contracting)	Yes
5	Size change of the cross section along the axis (expanding vs. expanding & contracting)	No
6	Symmetry of the cross section (reflectional vs. reflectional & rotational)	Yes
7	Symmetry of the cross section (reflectional & rotational vs. asymmetrical	Yes
8	Symmetry of the cross section (reflectional vs. asymmetrical)	Yes

Table 2. Summarized results of Experiments 1 through 8.

Experiment 1 tested whether axis curvature (straight vs. curved) is used to define the visual primitives used in object recognition, and the results suggested that axis curvature is used to define the basic set visual primitives used in object recognition.

Experiment 2 tested whether the edge curvature of the cross section (straight vs. curved) is used to define the visual primitives used in object recognition, and the results suggest that edge curvature is not used to define the visual primitives used in object recognition. When the analysis in Experiment 2 included all DDG trials, there was an interaction present, but the direction of the interaction suggested that LB had more difficulty with the DDG trials than with the DSG trials, which suggests that she was unable to use her categorical recognition system to make the distinction between the visual primitives defined by straight or curved axes. Even when controlling for the difficulty of the DDG trials, the was no significant interaction between task and participants, suggesting that the object recognition system does not recognize visual primitives defined by straight or curved axes as different from one another. This suggests that the shape recognition system does not make a categorical distinction between visual primitives that might be defined as a brick and a cylinder. One point worth noting, but for which there is currently no satisfactory explanation, is that LB's performance on the DSG trials in Experiment 2 was abnormally high, and had her performance on the DSG trials been more similar to her performances on the DSG trials of the other experiments, there may have been an interaction present suggesting that axis curvature is used to define the visual primitives used in object recognition.

Experiment 3 tested whether the size change of the cross section along the length of the axis (constant vs. expanding) is used to define the visual primitives used in object recognition, and the results suggest that it is. Another interesting point regarding Experiment 3 is that when the analysis included all of the DDG trials, the controls actually performed better on the DSG trials than they did on the DDG trials, whereas LB performed worse on the DSG trials than on the DDG trials (see Figure 16), providing additional evidence that LB's performance deficit patterns relative to those of controls are not due simply to task difficulty.

Experiment 4 tested whether the size change of the cross section along the length of the axis (constant vs. expanding & contracting) is used to define the visual primitives used in object recognition, and the results suggest that this distinction is used to define the visual primitives used in object recognition. Although when analyzed with all of the DDG trials included, there was no significant interaction between task and participant, when the analysis included only large-geon change DDG trials, an interaction appeared supporting the inclusion of size change (expanding vs. expanding & contracting) as a feature used to define the visual primitives used in object recognition. Given the results of Experiment 9, the interaction mentioned provides reasonable justification for inclusion of this feature as a defining feature of visual primitives.

Experiment 5 tested whether the size change of the cross section along the length of the axis (expanding vs. expanding and contracting) is used to define the visual primitives used in object recognition, and the results suggest that this feature is not used to define the visual primitives used in object recognition. Analyses from both the all DDG and large-geon only DDG conditions produced interactions showing that LB found DDG discrimination more difficult than DSG discriminations, suggesting that she was unable to distinguish between objects defined by expanding vs. expanding and contracting cross sections through the use of her categorical recognition system. This suggests that the shape recognition system does not make a categorical distinction between visual primitives that might be defined as a cone and a football. The conclusion from Experiment 5 is that the size change of the cross section (expanding vs. expanding and contracting) is not a feature used to define visual primitives used in object recognition.

Experiment 6 tested whether cross section symmetry (reflectional vs. reflectional and rotational) is used to define the visual primitives used in object recognition, and despite the relative difficulty of the DDG trials in Experiment 6, the results indicate that cross section symmetry (reflectional vs. reflectional and rotational) is used to define the visual primitives used in object recognition.

Experiment 7 tested whether the symmetry of the cross section (reflectional and rotational vs. asymmetrical) is used to define the visual primitives used in object recognition. The results from Experiment 7 indicate that the symmetry of the cross section (reflectional and rotational vs. asymmetrical) is used to define visual primitives used in object recognition. The results from Experiment 7, like those from Experiment 3, also indicate that whereas controls performed worse on the DDG trials than on the DSG trials, LB performed worse on the DSG trials than on the DDG trials (in the analysis including all DDG trials, as well as the analysis including large-geon only DDG trials), once again providing additional evidence that LB's pattern of results relative to controls is not an artifact of task difficulty (see Figures 28 and 29).

Experiment 8 tested whether the symmetry of the cross section (reflectional vs. asymmetrical) is used to define visual primitives used in object recognition, and the results strongly suggest that the symmetry of the cross section (reflectional vs. asymmetrical) is used to define visual primitives used in object recognition.

Experiment 9 was added to the original eight experiments to test the hypothesis that LB's poor performance on the DDG trials, which included changes to both the large and small geons, was a result of incomplete encoding of the small geon due to her visual field deficits. The results suggest that if given more time to fully scan and encode the initial image of presentation, that LB's performance on the DDG trials will rebound to levels similar (albeit slightly worse) to those of the controls on the DDG trials.

The nine experiments presented here provide the first empirical test of the visual primitives used for basic level object recognition. Biederman's (1987) geons represent hypothetical visual primitives based on computational considerations (such as viewpoint invariance) of the properties most likely to be used to define visual primitives. While there is some room for interpretation of the results of the nine studies presented here, much of the data clearly indicates that all of the features proposed by Biederman (see Figure 1) except curvature of the cross section, and the size change of the cross section (expanding vs. expanding and contracting) are used to define visual primitives used in object recognition. Although most of the features proposed by Biederman are empirically supported by the studies presented here, the number of Biederman's geons that can be generated by the remaining features, after removing cross section curvature and expanding vs. expanding and contracting cross sections drops from 36 to 12 geons. By removing cross section curvature, which assumed only two possible values, 18 of the geons are automatically removed, or in other words, are automatically merged with their straight or curved cross section counter-part. Similarly, by removing one of the three possible ways in which the size of the cross section can be defined, one third of the remaining geons are eliminated.

Future Directions

Subsequent investigations of the visual primitives used in object recognition, particularly those studies involving prosopagnosic patients, may benefit from a number of considerations derived from the results of the current studies. First, given the high co-occurrence of prosopagnosia and visual field deficits, it is clearly necessary to provide ample scanning (and hence, encoding) time when presenting visual images for comparison. Experiment 9 clearly indicated that the brief duration of the initially presented stimulus in each of these experiments was influencing the error rates of patient LB. Another strategy for dealing with poor encoding of two-part objects may be to conduct a similar study using individual visual primitives as stimuli, rather than two-part objects. Another method yet may be to generate the visual primitives as 2-dimensional images rather than as 3-dimensional, so as to ensure clearer images with sharper contrast (although this method is less appealing in that it loses some of its generalizability to actual 3-dimensional objects).

Despite the slight ambiguity of the results of Experiment 2, the results from the experiments presented here provide a strong foundation of evidence upon which the visual primitives used for object recognition can be identified. The next step toward definitively identifying which primitives are used by the structural descriptions that perform object recognition is to attempt a replication of the results using some of the variations of the current paradigm that are suggested in the preceding paragraph.

APPENDIX

Experiment	DSG Trials		DDG Trials (Large Geon Change)		DDG Trials (Small Geon Change)	
	LB	Controls	LB	Controls	LB	Controls
1	1704.6	776.5	1391.6	709.3	1749.9	743.8
2	1508.2	738.1	1381.7	701.2	1452.9	724.9
3	1611.9	637.0	1331.6	635.7	1385.3	654.5
4	1561.4	654.3	1561.4	646.7	1591.0	670.2
5	1459.9	649.7	1661.3	647.6	1739.0	686.7
6	1626.1	725.5	1367.4	668.6	2024.4	779.9
7	1808.1	629.3	1646.3	640.5	1647.5	652.5
8	1648.4	620.8	1436.0	586.8	1477.2	631.1
9	2163.0	629.3	1714.3	640.5	2081.6	652.5

Appendix. Reaction time data (in milliseconds) for Experiments 1 through 9. DSG trials are those trials in which both objects were composed of the same geons. DDG (Large Geon Change) trials are those trials in which only the larger of the two geons changed, and DDG (Small Geon Change) trials are those trials in which only the smaller of the two geons changed.

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